Patent Landscape Report

Decarbonizing Heavy-Duty Road Transport

IRENA
International Renewable Energy Agency

WIPO
WORLD INTELLECTUAL PROPERTY ORGANIZATION

Patent
Landscape
Report

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ISBN: 978-92-805-3957-8 (print)
ISBN: 978-92-805-3956-1 (online)

ISSN: 2790-7007 (print)
ISSN: 2790-7015 (online)

Suggested citation: World Intellectual Property Organization (WIPO) and International Renewable Energy Agency (IRENA) (2026). *Patent Landscape Report: Decarbonizing Heavy-Duty Road Transport*. Geneva: WIPO. DOI: 10.34667/tind.60159

Cover: Getty Images
WIPO Publication No. 1092EN/26

First published 2026

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Acknowledgments

This Patent Landscape Report on Decarbonizing Heavy-Duty Road Transport was prepared under the stewardship of Marco Alemán (Assistant Director General, IP and Innovation Ecosystems Sector) and the direction of Andrew Czajkowski (Acting Senior Director, Technology and Innovation Support Division), and was led by Christopher Harrison (Patent Analytics Manager, IP Analytics Section, Technology and Innovation Support Division), with the generous financial support of Funds-In-Trust Japan Industrial Property Global provided by the Japan Patent Office.

The report was prepared by a project team led by Christopher Harrison that included Lakshmi Supriya (Patent Analytics Officer), Hong Kan (Patent Analytics Officer), Ekrem Çakay (Fellow), Brianne Nicole Sanchez (Young Expert) and Pooyan Piredeir (former Young Expert) from the IP Analytics Section, Technology and Innovation Support Division, as well as Kai Gramke, Jochen Spuck and Klaus Jank (all from EconSight).

Our sincere thanks to our project partners at IRENA (International Renewable Energy Agency), in particular James Walker (Team Lead – Renewable Gases), Gayathri Prakash (Programme Officer, Innovation and End Use Sectors) and Jaidev Dhavle (Associate Programme Officer, Innovation for the Energy Transition). A special thanks also to Jens Hügel (Senior Adviser, IRU – International Road Transport Union) and Thibault Villien de Gabiole (Lead, Industry Decarbonization–Trucking, World Economic Forum) for their invaluable expert contribution to the report, as well as Marie-Anne Cervoni, Romaine Mouton, Hamza Guirrou and John Kidd (all from IRU – International Road Transport Union). The preparation of this report benefited from the expert review and comments of Abdullah Fahad, Arno van den Bos, Begonia Figueroa, Bilal Hussain, Jinlei Feng, Kamlesh Dookayka, Karan Kochhar, Mengzhu Xiao, Nadeem Goussous and Nolwazi Khumalo (all from IRENA), as well as Daniel Bowermaster (EPRI), Lars Martensson (Volvo) and Victor Bonilla (EBRD).

Our thanks also go to the WIPO editorial and design team led by Charlotte Beauchamp (Head of Publications and Design, Digital Engagement Service).

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Executive summary

Heavy-duty road transport – trucks and buses – is critical to the global economy and accounts for a substantial share of transport emissions, with trucks and buses responsible for 31% and 9% of road transport sector emissions, respectively. With approximately 94% of this sector currently powered by fossil fuels, decarbonization represents a crucial opportunity for emissions reduction.

This patent landscape report examines innovation trends in those technologies that are enabling the decarbonization of heavy-duty road transport, analyzing patent data from 2000 to 2024 across four core technology areas: low-emission energy sources (batteries, hydrogen fuel cells, hybrids, and alternative fuels), energy infrastructure, vehicle efficiency, and green digitalization.

The innovation landscape has undergone a fundamental transformation. The share of patents related to decarbonization technologies increased from around 7% of all heavy-duty road transport patents in 2000 to approximately 20% in 2024, with published patent families growing from around 1,200 to almost 15,400 annually. Electrification has emerged as the dominant pathway, evidenced by a large volume of patenting activity and strong growth across the entire electrification value chain. In 2024, batteries accounted for 73% of all low-emission energy source patents, while charging infrastructure and smart grids have lower levels of patenting in comparison, but have growth similar to what is being seen across other major technology areas.

Hydrogen technologies remain smaller in scale, but are gaining momentum, with patenting roughly doubling between 2019 and 2024. This suggests hydrogen could play a role in specific niches, particularly long-haul transport, though the technological and economic barriers remain substantial. Hybrid vehicle patenting has plateaued, increasingly overshadowed by fully electric solutions, while alternative low-carbon fuels show limited innovation activity, indicating they will likely remain niche or transitional solutions.

Patenting activity is geographically concentrated. China and the United States lead in absolute patent volumes. In China, annual patent publications have risen from just 11 in 2000 to around 7,300 in 2024, though Chinese inventors focus primarily on domestic patent protection. India has recorded even higher growth rates over recent years, albeit from a lower baseline, driven by government initiatives supporting electric bus deployment. Sweden and Germany demonstrate exceptionally high relative specialization across multiple decarbonization fields, reflecting their strong truck manufacturing industries.

Large automotive manufacturers and suppliers dominate innovation. Toyota leads patent rankings across all technology areas, followed by Volkswagen (including its subsidiary Traton, with the Scania and MAN brands), Hyundai, Ford, and major suppliers including Bosch and ZF. Notably, no universities or public research institutions appear among the top patent holders, underscoring the mature, industry-driven nature of heavy-duty road transport innovation.

The patent landscape reveals that technological foundations for decarbonizing heavy-duty road transport are advancing rapidly, with battery-electric solutions clearly dominant. A slowdown or plateauing of patenting activity was observed in 2024 across most technology areas, though whether this represents a temporary fluctuation or a longer-term shift remains to be seen.

Innovation activity is notably concentrated among major automotive players in a handful of countries, a pattern consistent with sector maturity. At the same time, while infrastructure patenting has grown dramatically, actual deployment remains behind the levels estimated to be necessary for large-scale fleet electrification, highlighting a gap between recent patenting activity and current infrastructure availability.

1 Introduction

This chapter introduces the decarbonization challenge facing heavy-duty road transport, highlighting the critical role of buses and trucks in global energy consumption and emissions. It outlines the report's analytical framework, focusing on four technology areas – low-emission powertrains, energy infrastructure, vehicle efficiency, and digital optimization – while explaining how patent analysis is used to identify innovation trends, key actors, and emerging opportunities.

Why decarbonization matters

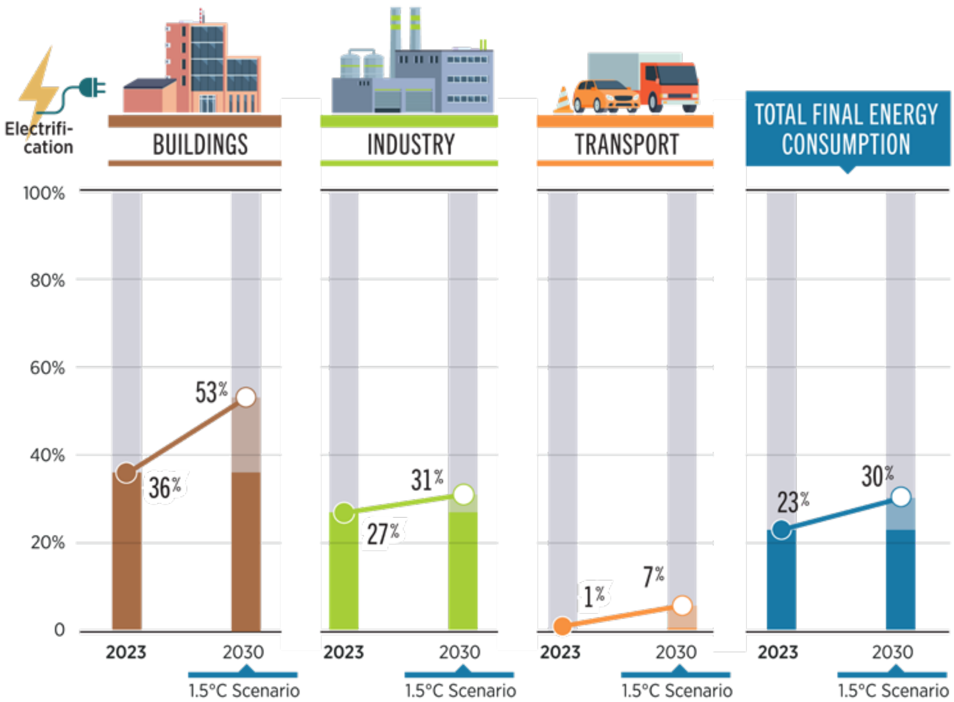
The energy transition continues to progress. Latest analysis by the International Renewable Energy Agency (IRENA) finds that 692 GW of new renewable capacity was added in 2025.[1] This was a record for a third straight year. But the 15.5% capacity increase this represents still falls short of the goal of tripling renewable capacity to 11.2 TW by 2030 agreed by the international community at COP28 in an effort to limit global warming to 1.5 degrees.[2]

A major sector where the penetration of alternative fuels needs to increase to support renewable goals is the electrification of end-use sectors. IRENA has found this approach to be one of the most effective decarbonization pathways. According to IRENA's analysis, the electrification rate of end-use sectors will need to increase from 23% in 2023 to 30% by 2030 to stay on the 1.5°C pathway.[3]

Some of the key solutions to electrification in end-use sectors include the deployment of electric heat pumps (up to 400% more efficient than traditional boilers), electric vehicles (up to 80% more efficient than internal combustion engines), and the introduction of efficient technologies in heavy industries, namely, steel, cement and chemicals. Figure 1.1 provides an overview of electrification rate required in each key end-use sector by 2030.

To be compliant with IRENA's 1.5°C pathway there is a strong impetus to increase the electrification rate across key end-use sectors viz. buildings, industry and transport.

Figure 1.1 Required electrification rate to meet 1.5°C Scenario in end use sectors by 2030



Note: TFEC is the total final energy consumption.
Source: IRENA, COP30 and GRA, 2025.

1 IRENA (2026). *Near-700 GW Surge in 2025 Proves Renewable Energy Resilience* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/News/pressreleases/2026/Apr/Near-700-GW-Surge-in-2025-Proves-Renewable-Energy-Resilience

2 IRENA, COP30 and GRA (2025). *Delivering on the UAE Consensus: Tracking Progress Toward Tripling Renewable Energy Capacity and Doubling Energy Efficiency by 2030*. Abu Dhabi: International Renewable Energy Agency, COP30 Presidency and Global Renewables Alliance. Available at: https://www.irena.org/Publications/2025/Oct/UAE-Consensus-2030-tripling-renewables-doubling-efficiency.

3 IEA, IRENA, UNSD, World Bank and WHO (2025). *Tracking SDG7: The Energy Progress Report 2025*. Washington, DC: World Bank, International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division and World Health Organization. Available at: https://www.irena.org/Publications/2025/Jun/Tracking-SDG-7-The-Energy-Progress-Report-2025; IRENA, COP30 and GRA (2025). *Delivering on the UAE Consensus: Tracking Progress Toward Tripling Renewable Energy Capacity and Doubling Energy Efficiency by 2030*. Abu Dhabi: International Renewable Energy Agency, COP30 Presidency and Global Renewables Alliance. Available at: https://www.irena.org/Publications/2025/Oct/UAE-Consensus-2030-tripling-renewables-doubling-efficiency

IRENA has found that progress in transport electrification in 2024 was significant, but remains insufficient. Under IRENA's 1.5°C scenario, electrification of transport sector total final energy consumption worldwide would need to have reached nearly 7% by 2030.[4] Road transport represents a crucial focus of efforts to decarbonize the transport sector. In 2023, road transport had an estimated energy consumption of 92 exajoules (EJ), accounting for 75% of the transport sector's and 20% of the world's total final energy consumption, respectively.[5] Currently, road transport accounts for over three-quarters of all transport emissions (6.2 Gt of CO_2 in 2023), or a fifth of global energy-related emissions – representing a key opportunity to introduce greening and energy efficient solutions.[6] It is also important to stress that most road transportation today – approximately 94% – is powered by fossil fuels, namely, petrol, diesel and natural gas.[7]

The decarbonization of the road transportation sector will require a systematic approach that leverages measures that include vehicle energy efficiency improvement, renewable energy-based electrification, better urban planning, and making public transport more accessible among others. Several of IRENA's recent analyses have found electrification of road transportation to be a promising avenue toward making this segment sustainable.[8][9][10]

When discussing electrification of road transport, a significant portion of the global narrative is focused on electric vehicles (EVs), especially passenger EVs, due to the fact that:

- lightweight duty vehicles is the most prevalent category of vehicle worldwide;
- many governments and policymakers have provided investments and subsidies for EVs because of their maturity and the rapid technological innovation undertaken by several original equipment manufacturers (OEMs); and
- technological progress and deployment in EVs have been very rapid.
- But overall market penetration is still limited, especially in developing countries.

However, while EVs are a crucial enabler of road transportation decarbonization, two often-overlooked segments are buses and heavy-duty trucks. These two segments need to be put in the spotlight in order to accelerate road transportation decarbonization efforts – especially given they account for 9% and 31%, respectively, of the road transport sector's global emissions.[11]

4 IRENA, COP30 and GRA (2025). *Delivering on the UAE Consensus: Tracking Progress Toward Tripling Renewable Energy Capacity and Doubling Energy Efficiency by 2030*. Abu Dhabi: International Renewable Energy Agency, COP30 Presidency and Global Renewables Alliance. Available at: https://www.irena.org/Publications/2025/Oct/UAE-Consensus-2030-tripling-renewables-doubling-efficiency.

5 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

6 IRENA (2024a). *Critical Materials: Batteries for Electric Vehicles*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

7 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

8 IRENA (2023). *Innovation Landscape for Smart Electrification: Decarbonising End-use Sectors with Renewable Power.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2023/Jun/Innovation-landscape-for-smart-electrification; IRENA (2024d). *Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7,*

9 International Renewable Energy Agency, Abu Dhabi;

10 Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Apr/IRENA_G7_Decarbonising_hard_to_abate_sectors_2024.pdf; IRENA (2024a). *Critical Materials: Batteries for Electric Vehicles*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

11 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

Jens Hügel, Senior Adviser, International Road Transport Union (IRU)

How IRU is helping to achieve net zero by 2050

The International Road Transport Union is helping the commercial road transport industry meet its objective of carbon neutrality by 2050. While highly disruptive and challenging for all stakeholders, the energy transition toward cleaner energy could allow industry greater resilience against its many other challenges such as digitalization of transport documents and driver shortages. IRU Green Compact is a pathway looking at the most pragmatic solutions to reducing bus and truck emissions. This involves working on greater transport efficiencies (vehicles, fleets, logistics and drivers) in order to ease the move toward alternative fuels, with the support of the right enabling conditions. As for buses, solutions exist to encourage a modal shift away from private cars and go even further in carbon reduction.

Buses

Mobility is a fundamental need of citizens worldwide. And while the lion's share is covered by private forms of transportation such as cars, buses are playing a major role in the public transportation system, especially within and between urban nodes. Beyond travel, buses also contribute toward education, jobs and economic development opportunities, especially for those individuals and communities unable to afford private transportation. In urban contexts, buses are the most efficient mode of transportation, allowing for greater passenger carrier capacities, as well as reducing road congestion.[12] In fact, a bus replaces 30 cars therefore bus and coach usage is a ready enabler of sustainable transport.

As of 2022 there were approximately 20 million buses on the road worldwide. This mode of transportation is essential for many small and medium-sized cities, as well as cities in emerging and developing markets, thanks to its ease of deployment and cost-efficiency. There is an expectation that the global bus fleet will grow as urbanization increases along with drives to encourage a shift toward public modes of transport. The popularity of rapid bus transit services that have lower capital costs is also expected to increase the demand for greater bus deployment.[13]

The need to make buses more sustainable arises from the high contribution they make toward road transport emissions – accounting for 500 million tonnes of direct CO_2 in 2022. Currently, most buses are powered by diesel engines and account for 25% of the black carbon emitted by the transport sector globally. Pollution arising from diesel buses has impacted health, especially in densely populated city areas.[14]

Heavy-duty freight

More often than not, trucks are the beginning and end of goods trade and commerce. A key element of the supply chain, they expedite the rapid transport of goods over land and answer the many needs of cargo owners. Trucks are to be found in all industries, moving industrial, agricultural and manufactured goods around the world. As of 2023, they comprised a fleet of approximately 50 million medium- and 35 million heavy-duty vehicles. Trucks also account for a third of global road transport emissions, especially in countries where the primary sector and industry are the primary economic drivers.[15]

12 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
13 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
14 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
15 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

While the longest journeying international freight is generally covered by the maritime industry, and sometimes by the aviation industry, trucks dominate the regional economy, moving 60% of surface goods worldwide.[16] Trucking intensity varies across nations, depending on infrastructure, alternative and sea access, as well as border agreements.

With global trade and gross domestic product (GDP) per capita expected to grow worldwide in the future, road transport is projected to expand, creating challenges for the road industry in meeting demand while at the same time reducing carbon emissions. Much like buses, trucks are heavily reliant on fossil fuels to provide power at the lowest cost and greatest uptime.

Objectives of this report

Given the importance of buses and heavy-duty trucks in the global transportation sector, the main purpose of this report is to highlight the innovations being developed to decarbonize these two road transportation modes. To do so, the report leverages patent data from global patent databases to elucidate broadly where innovations are occurring and, based on the trends observed, pinpoint market and technology gaps, as well as opportunities relevant to making these road transport modes sustainable and efficient.

This report is derived from WIPO's flagship *Technology Trends: Future of Transportation*[17] which was launched in February 2025 and aims to provide useful insights for transportation sector stakeholders interested in leveraging actions and initiatives to accelerate the decarbonization of buses and trucks – following a similar model to EVs.

The report examines the broad set of technologies contributing to the decarbonization of heavy-duty road transport and identifies those countries, companies and institutions driving innovation in this field. The patent analysis focuses on four core technology areas critical to reducing greenhouse gas emissions from buses and heavy-duty trucks (Figure 1.2).

Four core technology areas were identified to define the taxonomy used for this report

Figure 1.2 Technology trends shaping the decarbonization of heavy-duty road transport

Low-emission energy sources	Energy infrastructure	Vehicle efficiency	Fleet digitalization
Batteries	Hydrogen infrastructure	Advanced power- and drivetrains	
Hybrids	Charging and smart grids	Vehicle design and tires	
Fuel cells		Advanced materials	
Alternative fuels			

Source: WIPO.

The transition away from internal combustion engines powered by fossil fuels is the central pillar of heavy-duty road transport decarbonization. Key technological pathways include battery-electric powertrains, hydrogen fuel cells, hybrid powertrains, and combustion engines operating on low-carbon fuels such as biofuels, synthetic fuels and natural gas. These technologies differ significantly in their maturity, infrastructure requirements, and suitability for specific use cases, but together they define the main options for reducing tailpipe emissions in heavy-duty vehicles.

16 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
17 WIPO (2025). *WIPO Technology Trends Report 2025: The Future of Transportation*. Geneva: World Intellectual Property Organization. Available at: https://www.wipo.int/web-publications/wipo-technology-trends-future-of-transportation/en/index.html.

Complementary to low-emission vehicles is the need for a robust, scalable energy infrastructure capable of supporting widespread deployment. The operational feasibility of low-emission buses and trucks depends on the availability and performance of energy distribution networks, including high-power charging systems, smart grids, as well as hydrogen production, storage and refueling infrastructure.

Improvements in vehicle efficiency remain a crucial supporting strategy for decarbonizing heavy-duty road transport, irrespective of the underlying energy source. Efficiency gains directly reduce the amount of energy required to transport goods and passengers, thereby lowering operating costs and lifecycle greenhouse gas emissions. Relevant technologies include advances in electric powertrains and drivetrains, vehicle aerodynamics, lightweight and high-performance materials, and reductions in tire rolling resistance.

Finally, digital technologies and data-driven fleet optimization offer additional opportunities to reduce emissions through improved vehicle operation and system-level efficiency. Applications such as platooning, smart routing, and vehicle-to-infrastructure communication can reduce energy consumption by minimizing idle time, smoothing driving patterns, anticipating charging or refueling needs, and improving asset utilization. While these technologies do not replace the need for low-emission energy sources, they play an important complementary role by optimizing the energy use across heavy-duty vehicle fleets.

Together, these four technology areas form the analytical framework for the patent-based assessment presented in the following chapters, which examine innovation trends, leading actors, and the geographical patterns shaping the decarbonization of buses and heavy-duty trucks.

2 Decarbonizing heavy-duty road transport: global patent trends

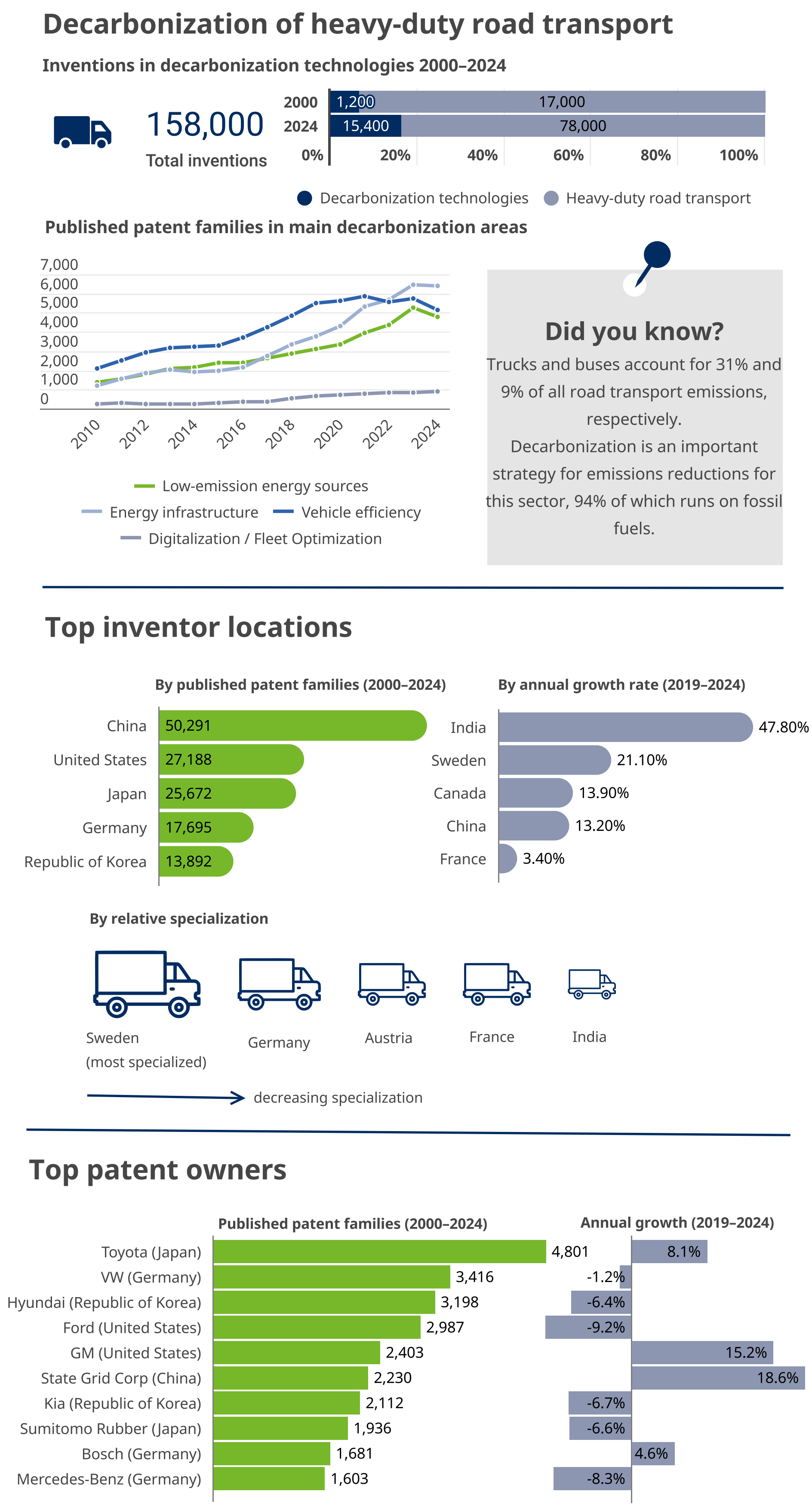
Global patenting trends in technologies supporting the decarbonization of heavy-duty road transport are examined in this chapter. It highlights growth across key technology areas, the dominance of electrification and batteries, and the leading countries and companies driving innovation, offering insight into the technological momentum shaping low-emission buses and trucks.

Key findings

The main findings of this report in terms of global patenting activity in the main decarbonization areas across heavy-duty road transport are as follows:

- Decarbonization technologies have gained significant importance within the heavy-duty road transport innovation landscape. Since 2000, the share of patents related to decarbonization technologies has increased from around 7% of all heavy-duty road transport patents to approximately 20% in 2024, reflecting a clear shift in research priorities.
- The main research fields – energy infrastructure, vehicle efficiency, and low-emission energy sources – currently show comparable patenting activity. Each field accounted for roughly 5,000–6,000 published patent families in 2024. While patenting activity in vehicle efficiency technologies has stagnated over recent years, innovation in low-emission energy sources and energy infrastructure continues to show strong growth, aside from a dip in 2024.
- Electrification is the dominant decarbonization pathway in heavy-duty road transport. This is evidenced by the high volume and growth of patenting activity across the electrification value chain, including batteries as energy sources, charging and smart-grids in energy infrastructure, and advanced electric power- and drive-trains in vehicle efficiency. These trends indicate that battery-electric solutions are likely to remain the central pillar of heavy-duty road transport decarbonization in coming years.
- Patenting activity related to hybrid heavy-duty vehicles continues at a meaningful level, reflecting their role as a transitional technology, particularly for urban and regional applications. However, patent volumes have plateaued in recent years, indicating that this technology is increasingly being overshadowed by fully electric solutions.
- Hydrogen technologies remain smaller in scale, but are gaining momentum. Patenting related to fuel cells and hydrogen infrastructure has accelerated since around 2019. Continued technological progress could enable hydrogen to play a role in specific heavy-duty niches, particularly long-haul transport.
- Innovation activity is geographically concentrated. China, the United States, Japan, Germany and the Republic of Korea dominate patenting in decarbonization technologies in heavy-duty road transport. China has emerged as the leading location due to its strong growth dynamics. India has recorded even higher recent growth rates, albeit from a much lower absolute level. Sweden and Germany stand out for having an exceptionally high level of relative research specialization across multiple decarbonization fields within heavy-duty road transport.
- Large automotive manufacturers and suppliers are the central innovation actors. Since 2000, Toyota (including its subsidiaries Hino Motors and Daihatsu), Volkswagen (including its subsidiary Traton, with the Scania and MAN brands) and Hyundai have published the highest number of patent families across those decarbonization technologies analyzed.

Figure 2.1 A summary of the global patenting trends in decarbonization technologies for heavy-duty road transport



Note: All data are based on counts of published patent families.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Development of decarbonization technologies in heavy-duty road transport

Over the past 25 years, patenting activity related to the decarbonization of heavy-duty road transport has expanded significantly, increasing from around 1,200 published patent families in 2000 to almost 15,400 in 2024 (Figure 2.1). Over the same period, total patenting activity in heavy-duty road transport, including non-decarbonization areas such as conventional combustion engine technologies, rose from 17,000 to almost 78,000 patent families. As a result of the comparatively stronger growth in decarbonization-related research, its share of total heavy-duty road transport patents increased from 7% in 2000 to around 20% in 2024.

Over the same time period, regulations have pushed truck original equipment manufacturers (OEMs) into developing new engine technologies to lower harmful emissions while also decreasing fuel consumption.[1] Gearboxes and data exchange networks have also been developed to help drivers perform tasks, while also enhancing engine performance.[2] Many lawmakers worldwide also require heavy-duty vehicles to be safer on the roads.[3] Following on from the adoption of disc brakes in the 2000s, trucks today often employ radar and cameras to improve vehicle dynamics and reduce accident rates.

This outperformance has, however, largely been driven by developments in the 2000s. Since around 2012, patent growth rates both in decarbonization technologies and heavy-duty road transport overall have been broadly similar. Reinvigorating innovation dynamics in decarbonization technologies is likely to be a key prerequisite for meeting ambitious climate objectives in heavy-duty road transport.

Development in the main decarbonization areas

A comparison of the main decarbonization research areas within heavy-duty road transport shows that energy infrastructure, vehicle efficiency and low-emission energy sources currently exhibit a broadly comparable patenting scale. In 2024, each of these fields accounted for approximately 5,000–6,000 published patent families, up from around 750 patent families in vehicle efficiency technologies and fewer than 400 in both energy infrastructure and low-emission energy sources in 2000. While patenting activity in vehicle efficiency technologies has largely stagnated over recent years, innovation in low-emission energy sources and energy infrastructure has continued to grow strongly, with the exception of a dip in 2024. Patenting activity in green digitalization technologies – defined here as digital inventions that contribute to reducing CO_2 emissions in heavy-duty road transport – has also increased steadily, albeit from a much lower absolute level. These technologies play a crucial role in decarbonization efforts, by optimizing the use and integration of low-emission energy sources and energy infrastructure, as well as improving the efficiency of heavy-duty trucks and buses.

In the area of low-emission energy sources, patenting activity related to battery-electric vehicles has clearly emerged as the dominant research focus. Hybrid vehicles continue to attract substantial research activity, but growth has been comparatively modest, perhaps in Europe because European Union regulations are unfavorable to such technology (EU, 2017/2400). Patenting in hydrogen technologies for trucks and buses remains smaller in scale than for battery-electric and hybrid vehicles, although activity has accelerated, with annual patent counts roughly doubling between 2019 and 2024. In contrast, alternative fuels have generated only limited patenting activity over the past two decades.

1 European Union (2024). Vehicle emissions and battery durability (Euro 7): Technical requirements and certification rules. Publications Office of the European Union. Available at: https://eur-lex.europa.eu/EN/legal-content/summary/vehicle-emissions-and-battery-durability-euro-7-technical-requirements-and-certification-rules.html.
2 Daimler-Truck (2024). Safe, fast and simple: Daimler Truck and Linde set new standard for liquid hydrogen refueling technology. Available at: https://www.daimlertruck.com/en/newsroom/pressrelease/predictive-powertrain-control-ppc-10-questions-and-answers-about-the-predictive-cruise-control-from-mercedes-benz-trucks-46682406
3 European Union (2019). Regulation (EU) 2019/2144 of the European Parliament and of the Council (Document 32019R2144, 27 November 2019). Publications Office of the European Union. Available at: https://eur-lex.europa.eu/eli/reg/2019/2144/oj/eng.

A similar pattern is observed in energy infrastructure, where innovations in charging technologies and smart grids have reached a larger scale than have hydrogen infrastructure technologies such as pipelines, storage, and refueling stations, despite a recent pickup in hydrogen-related patenting.

Within vehicle efficiency technologies, innovations in electric motors and gearings also dominate the research landscape, although patent growth in this area has been subdued over the past five years. Vehicle design and tire technologies continue to account for sizeable research activity, but show limited growth, while advanced materials exhibit the weakest performance in terms of both patenting levels and growth dynamics.

As mentioned, research activity in digitalization and fleet optimization technologies has expanded steadily over the past decade. However, focusing on growth rates alone obscures significant differences in the absolute scale of patenting across decarbonization technologies.

To address this, the WIPO Patent Momentum Indicator[4] combines patenting levels and growth dynamics over the last five years into a single score to identify those technologies with the strongest innovation momentum (Figure 2.2). The indicator shows that batteries, as well as charging technologies and smart grid infrastructure, have exhibited by far the strongest patent momentum over recent years.

Batteries and charging/smart grid technologies have the strongest patent momentum

Figure 2.2 WIPO Patent Momentum Indicator for decarbonization technologies in heavy-duty road transport, 2019–2024

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

4 See Appendix A.2 for full details

Top patent locations

Driven by strong patent growth over the last decades, China has become the top patenting location for decarbonization technologies in heavy-duty road transport. Between 2000 and 2024, annual patent family publications by Chinese inventors rose from just 11 to around 7,300. Over the past five years alone (2020–2024), China has published more than 32,000 patent families. Unlike in most other leading research locations, Chinese inventors tend to focus primarily on domestic patent protection.

The United States is the second most important research location for decarbonization technologies in heavy-duty road transport, with 8,755 patent families published since 2020. Japan (6,559), Germany (6,297) and the Republic of Korea (4,390) follow. However, patent growth in these key research locations has been subdued in recent years, with modest growth in the Republic of Korea, Germany, and the United States, and a decline in Japan. In contrast, India has experienced exceptionally strong patent growth, propelling it to sixth place in the ranking, with 3,113 published patent families since 2020.

Sweden and Germany stand out for having exceptionally high levels of relative specialization in decarbonization technologies for heavy-duty road transport, most likely because both countries are home to the major European OEM companies. It is also noteworthy that China's level of specialization is lower than that of other leading research locations.

Top patent owners

Toyota (including its subsidiaries Hino Motors and Daihatsu) leads the ranking of the top patent owners in heavy-duty decarbonization technologies, with around 4,800 published patent families between 2000 and 2024.[5] Other Japanese firms represented in the top 20 include Honda, Denso, Sumitomo Rubber and Bridgestone. German automotive manufacturers and suppliers account for six positions in the ranking, namely, Volkswagen (VW) (including its subsidiary Traton, with the Scania and MAN brands), Bosch, Mercedes-Benz, BMW, ZF, and Schaeffler. The United States is represented by Ford and General Motors (GM), while the Republic of Korea's leading automotive groups, Hyundai and Kia, also rank among the top 20.

Three Chinese companies appear in the top 20: State Grid, BYD and Geely. The Utility State Grid – a leading innovator in charging and smart grid solutions – is the only company in the top 20 whose core business lies outside the automotive sector. Sweden's Volvo and France's Michelin also feature in the top 20 ranking, making them the sole companies headquartered outside the five dominant innovation regions.

Notably, no universities or public research institutions appear among the leading patent owners. Tsinghua University in China is the highest-ranked academic institution, placed 61st, with 354 relevant patent families published since 2000. This underscores the mature and highly industrial nature of heavy-duty road transport innovation, which is predominantly driven by corporate research and development.

Looking at recent dynamics, Volvo, ZF, Geely, BYD, Kia, State Grid, and General Motors stand out, with high patent growth rates since 2019, whereas patenting activity at Michelin has declined noticeably over the same period.

5 The composition of the ranking is expected to change from 2026 onward following the announced integration of Hino Motors (a Toyota subsidiary) and Mitsubishi Fuso (a Daimler Truck subsidiary) into a new independent company, ARCHION, which is scheduled to commence operations in April 2026.

3 Energy sources

Low-emission energy sources are central to decarbonizing heavy-duty road transport, with innovation spanning battery-electric systems, hydrogen fuel cells, hybrid powertrains and alternative fuels. Patent analysis in this chapter shows rapid technological progress, dominated by batteries, while highlighting regional innovation patterns, leading research locations and the accelerating pace of invention in cleaner vehicle energy systems.

Transitioning away from internal combustion engines

A key element in the process of decarbonizing heavy-duty road transport is the transition from internal combustion engines running on fossil fuels to more sustainable energy sources. These include battery-electric systems, hydrogen fuel cells, hybrid powertrains, as well as combustion engines operating on low-carbon fuels, such as biofuels, e-fuels and natural gas. Each of these technologies contributes to reducing greenhouse gas emissions in a different way and has distinct technical and economic characteristics:

- Battery-electric trucks and buses (BEVs) are currently the most advanced zero-emission option for short- and medium-haul operations, particularly on routes with predictable distances. They offer high energy efficiency, zero tailpipe emissions and low operating costs. However, adoption remains constrained by high upfront costs, limited payload capacity due to battery weight, and lower uptime due to charging time and the lack of an extensive charging infrastructure. As battery energy density improves, costs decline and networks expand, battery-electric trucks are expected to become the dominant solution for short- and medium-haul freight, and increasingly competitive for longer distances. According to the International Energy Agency (IEA), global sales of electric buses surpassed 70,000 in 2024, while electric truck sales exceeded 90,000, accounting for approximately 6% of total bus and 2% of total truck sales.[1] While electric heavy-duty vehicles already play a major role in China and certain European countries, they still constitute a very small percentage of the total fleet in most other countries.
- Hydrogen fuel cell trucks have the potential to become a viable option for long-haul operations where battery-electric trucks face range or charging constraints. They offer faster refueling and have the potential for longer driving ranges than BEVs, and comparable payload and performance to diesel trucks while emitting only water vapor. The technology, however, remains expensive due to high vehicle and hydrogen production costs, limited refueling infrastructure and the need for low-carbon hydrogen supply. A key disadvantage of hydrogen fuel cell trucks is their lower overall energy efficiency. Because the hydrogen production and conversion chain has substantial energy losses, fuel-cell trucks typically require around two times more energy per kilometer compared to battery-electric trucks.[2] Global sales of fuel cell trucks reached only around 3,000 units in 2023 – over 90% of which were in China.[3] While current deployment is very small, ongoing technological improvements and supportive policy frameworks could make hydrogen a relevant option for long-haul trucking in the coming decade.[4]
- Hybrid heavy-duty trucks and buses that combine a conventional internal combustion engine with one or more electric engines offer moderate fuel savings and emissions reductions, especially in urban or stop-and-go operations. While they do not offer zero tailpipe emissions, they serve as a practical transitional technology toward full electrification without requiring dedicated charging infrastructure. However, their advantages disappear on long-haul routes, and the dual-powertrain design adds cost, weight and complexity.
- The use of alternative low-emission fuels, such as biofuels, synthetic fuels and natural gas, for heavy-duty road vehicles can reduce greenhouse gas emissions while utilizing existing engines and refueling networks, offering an immediate drop-in solution for decarbonization. However, the production of synthetic fuels is energy-intensive and often costly and the potential climate benefits depend primarily on the use of renewable energy in their production. The use of biofuels is restricted due to a lack of sustainably available feedstock.

1 IEA (2025a). IEA Global EV Outlook 2025. International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025/trends-in-heavy-duty-electric-vehicles.
2 Basma, H. and F. Rodríguez (2022). Fuel Cell Electric Tractor-Trailers: Technology Overview and Fuel Economy. *ICCT Working Paper 2022-23*. International Council on Clean Transportation. Available at: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-1-jul22.pdf.
3 BloombergNEF (2024b). Zero-emission commercial vehicles: The time is now. Available at: https://assets.bbhub.io/professional/sites/24/Commercial_ZEV_Factbook.pdf.
4 Clean Air Task Force (2023). *Zero Emission Long-Haul Heavy-Duty Trucking*. Available at: https://cdn.catf.us/wp-content/uploads/2023/03/13145547/zero-emission-long-haul-heavy-duty-trucking-report.pdf.

Total cost of ownership

Total cost of ownership (TCO) is a key metric in the heavy-duty road transport sector, helping to assess the competitiveness of low-emission trucks and buses compared to traditional, fossil fuel trucks and buses. TCO is calculated by adding together all the costs involved in acquiring, operating, maintaining and disposing of a vehicle over its useful life, and then expressing these costs on a per-kilometer or per-year basis. A TCO analysis helps businesses optimize costs and make informed decisions about fleet management.

However, because heavy-duty vehicles operate in different duty cycles, TCO results are vocation dependent. Last-mile delivery, urban buses and long-haul trucks, for example, each produce a different balance of upfront capital, energy consumption and utilization. Regional differences also play a role since battery costs and the availability of charging or hydrogen infrastructure influence TCO.

Currently, diesel trucks and buses generally have the lowest initial purchase price and often the highest residual value, while their operating fuel costs fluctuate with the price of diesel.[5] Battery-electric vehicles currently have higher purchase prices yet their lower electricity cost per kilometer and reduced maintenance mean they already have competitive TCO in certain markets. Hydrogen fuel-cell trucks today face both high upfront vehicle prices and high fuel costs because low-carbon hydrogen remains expensive and infrastructure is sparse.[6] Hybrid heavy-duty vehicles usually sit between diesel and battery-electric vehicles on both capital cost and operating cost: hybrids add components and complexity that raise purchase price but in urban stop-and-go duty cycles regenerative braking and electric engines lower fuel consumption. E-fuels and biofuels typically do not require new vehicle purchases or widespread changes to refueling hardware, so upfront costs are low, but their fuel price premium is the crucial TCO factor.

According to estimates from the IEA for 2024, the TCO of battery-electric trucks is already lower in China than that of diesel trucks in several market segments due to the low cost of electric vehicle (EV) batteries in China.[7] The IEA estimates the TCO for a typical heavy-duty battery-electric truck in 2024 to be around 0.8 USD/km in China, compared with 0.9 USD/km for a diesel truck. In the European Union (EU), TCO levels are estimated to be notably higher, at 1.6 USD/km for a battery-electric truck versus 1.5 USD/km for diesel. The United States shows the highest costs due to higher electricity and infrastructure costs, with 1.9 USD/km for a battery-electric truck compared to 1.6 USD/km for diesel. Hydrogen fuel-cell heavy-duty trucks remain considerably more expensive across all regions analyzed, with TCO of 1.3 USD/km in China and 2.3 USD/km in both the European Union and the United States.

Decarbonization brings a green premium as new technologies often result in greater TCO, that needs to be mitigated to avoid cargo owners paying higher freight rates. While intermediary measures, such as purchase incentives and tolling exemption, could bring zero-emission technologies' TCO below that of diesel, it is expected that the combined effect of an increase for diesel and a decrease of alternative's TCO will result in TCO parity in the future. The technological advancements in heavy-duty road transport technologies, which are the focus of this report, will play a significant part in enhancing competitiveness.

5 Kemlin, P. (2024). Why a truck's total cost of ownership is so vital when it comes to alternative drivelines. Volvo. Available at: https://www.volvotrucks.com/en-en/news-stories/insights/articles/2024/sep/how-alternative-fuels-impact-total-cost-of-ownership.html.

6 Energy Innovation (2025). *Delivering Affordability: The Emerging Cost Advantage of Battery Electric Heavy-Duty Trucks and U.S. Policy Strategies to Unlock Their Full Economic Potential*. Available at: https://energyinnovation.org/wp-content/uploads/Delivering-Affordability-Emerging-Cost-Advantages-of-Battery-Electric-Heavy-Duty-Trucks.pdf.

7 IEA (2025d). Trends in heavy-duty electric vehicles. In *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025/trends-in-heavy-duty-electric-vehicles.

Global patent development

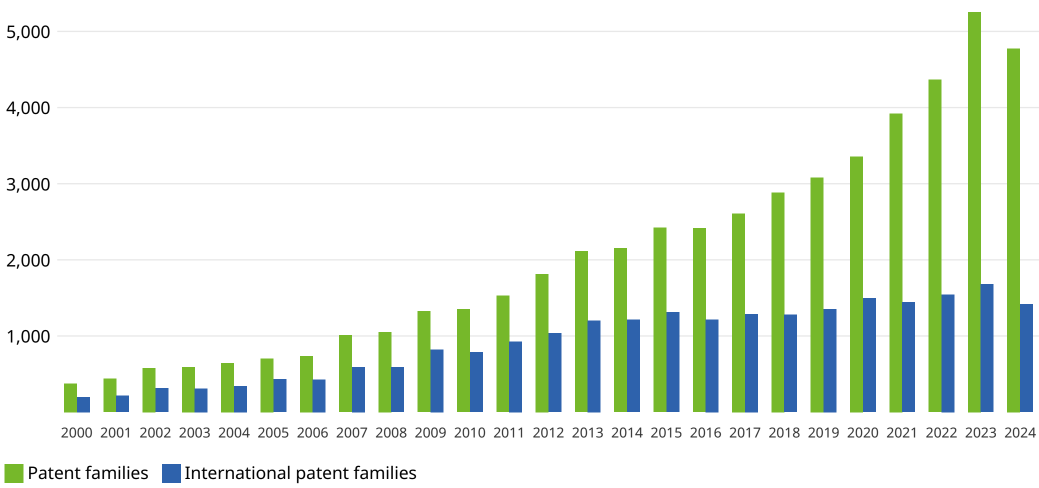
Global patent development in low-emission energy sources

Significant technological advances in low-emission energy sources for vehicles are clearly reflected in the impressive increase in patenting activity over the last 25 years (Figure 3.1). Between 2000 and 2024, the number of published patent families in the field of low-emission energy sources for heavy-duty road vehicles increased from fewer than 380 annually to almost 4,800. Analysis of international patent families (IPF) – inventions that are protected in multiple countries – reveals that the numbers increased from under 200 annually to around 1,400 within the same period.

However, 2024 saw a dip in patenting activity. This drop was probably influenced by increasing overcapacity in the production of batteries, particularly in China.[8] Overcapacity squeezes profit margins in two ways. First, when industry capacity exceeds demand, producers engage in price competition, reducing margins. Second, when individual firms operate below their installed capacity, fixed costs are spread over fewer units, increasing per-unit costs and further lowering margins. Faced with these pressures, many companies may have shifted their focus from groundbreaking research and development to cutting costs and optimizing large-scale production. This interpretation is supported by evidence that investment in new battery production capacity in China also slowed in 2024, suggesting that manufacturers were prioritizing efficiency and consolidation over expansion and innovation.[9] On a positive note, overcapacity in battery production has also contributed to declining battery costs, helping to make electric heavy-duty vehicles more cost-competitive with their diesel counterparts.

Patenting activity in low-emission energy sources for heavy-duty road transport has risen sharply over the last 25 years

Figure 3.1 Published patent families in low-emission energy sources for heavy-duty road transport by earliest publication year, 2000–2024



Note: International patent families represent inventions that are protected in multiple jurisdictions.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

8 BloombergNEF (2024a). China already makes as many batteries as the entire world wants. Available at: https://about.bnef.com/insights/clean-transport/china-already-makes-as-many-batteries-as-the-entire-world-wants.
9 Rhodium Group (2025). *Global Clean Investment Monitor: Electric Vehicles and Batteries*. Available at: https://rhg.com/wp-content/uploads/2025/06/Global-Clean-Investment-Monitor-Electric-Vehicles-and-Batteries.pdf.

Overview of the four key low-emission energy sources

Taking a closer look at patenting activities in the four key low-emission energy sources (Figure 3.2), it becomes evident that battery research dominates research activities within heavy-duty road transport. The number of published patent families in this field jumped from 137 in 2000 to 3,511 in 2024. Consequently, in 2024, the field of batteries accounted for 73% of all patent families in low-emission energy sources. Research focus areas therefore align with commercial trends, with battery-electric heavy-duty vehicles outselling other types of low-emission energy sources by a large margin.[10]

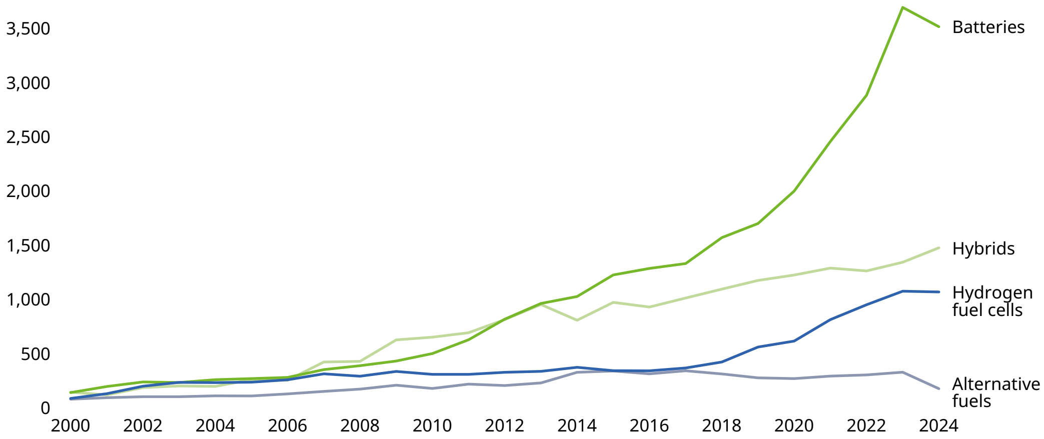
With 1,472 published patent families, hybrid heavy-duty vehicles were the second-largest field in terms of patent numbers in 2024. However, patenting activity has only increased moderately in recent years.

In contrast, patenting activity in hydrogen fuel cells for heavy-duty road transport has been more dynamic, with the number of patent families increasing threefold over the last 10 years (from 339 in 2015 to 1,065 in 2024).

Meanwhile, patenting activity in alternative fuels for heavy-duty road transport remained low over the entire period analyzed and even declined in 2024 (to just 173 patent families).

Global research activities focus on battery-electric heavy-duty road vehicles, but patent growth has recently picked up in hydrogen fuel cells

Figure 3.2 Published patent families in each of the low-emission energy sources for heavy-duty road transport by earliest publication year, 2000–2024



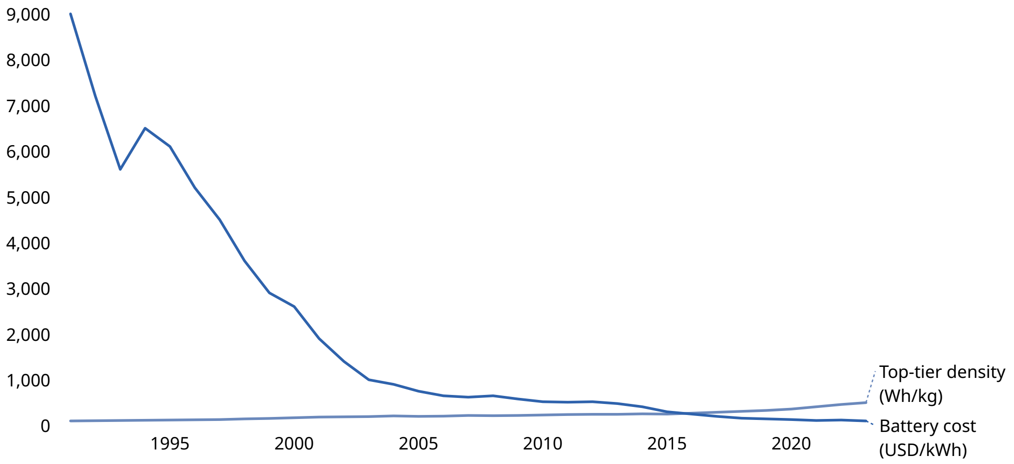
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Batteries for electric heavy-duty road transport vehicles

Over the past 25 years, battery systems for road vehicles have evolved from expensive, niche technologies into a commercially viable backbone for passenger cars, and increasingly for heavy-duty trucks and buses. From the late 1990s onward, lithium-ion chemistry emerged as the dominant solution, overtaking legacy battery types, such as lead-acid, nickel-cadmium and nickel-metal hydride (NiMH). Manufacturers have rapidly improved the energy density of lithium batteries while significantly decreasing costs by optimizing cell chemistry, pack design and production scale (Figure 3.3). These advances have enabled the early large-scale deployment of electric buses and regional distribution trucks.[11]

10 BloombergNEF (2024b). Zero-emission commercial vehicles: The time is now. Available at: https://assets.bbhub.io/professional/sites/24/Commercial_ZEV_Factbook.pdf.
11 D'Amico, S. and P. McCormick (2025). The Electric Slide: The history, 99% decline, and future of the Electric Stack. Available at: https://www.notboring.co/p/the-electric-slide.

Figure 3.3 Development of lithium battery costs and density, 1990–2023, costs in USD per kilowatt-hour, density in watt-hour per kilogram



Source: WIPO, based on data from Rupert Way (2026) based on Ziegler and Trancik, 2020https://pubs.rsc.org/en/content/articlelanding/2021/ee/d0ee02681f and BloombergNEF, 2023, and Avicenne Energy, with minor processing by Our World in Data (https://ourworldindata.org/grapher/price-of-lithium-ion-battery-cells).

The first lithium-ion batteries used in vehicles employed lithium cobalt oxide (LCO), nickel-cobalt-aluminium (NCA) or nickel-manganese-cobalt (NMC) cathodes with graphite anodes. However, the high cobalt content meant high costs and supply risks. During the 2010s, the trend shifted toward nickel-rich cathode formulations to increase energy density and reduce cobalt usage. Meanwhile, cost-sensitive sectors, including many heavy-duty vehicles, adopted lithium iron phosphate (LFP) cells and, more recently, lithium manganese iron phosphate (LMFP) cells.[12] Although LFP chemistry offers lower energy density than top-tier nickel-rich cells, it provides improved safety, a longer cycle life, a lower cost and a simpler supply chain. These attributes are well suited to buses and trucks, which require large energy capacity, safe thermal performance, a long life, fast or overnight depot charging, and high utilization. China has led the way in the early adoption of heavy-duty LFP batteries, with firms such as CATL and BYD scaling up the production of large-format modules and heavy-duty packs.

Currently, global demand for EV batteries is roughly evenly split between LFP and NMC chemistries. LFP is the fastest-growing segment, particularly dominant in China thanks to its lower cost and longer cycle life.[13] Looking ahead, several trends are set to influence the next phase of battery deployment for heavy-duty road transport. Improvements in chemistry and manufacturing are likely to continue: the cost of battery packs is forecast to decline further and energy density will improve, lowering the barrier for heavier vehicles and longer routes. A potential disruptor could be battery-swapping, which is gaining momentum in China,[14] allowing lower upfront costs for operators, but greater investments and battery needs for suppliers. Next-generation technologies – such as solid-state batteries, lithium-sulfur and sodium-ion batteries – are under active development and promise higher energy density and/or safety, but they still face manufacturing and technological challenges before they can be produced commercially. For heavy-duty use cases, incremental innovations for incumbent lithium-ion batteries, such as cell-to-body technology, more durable batteries and faster charging, are also likely to remain very important.

12 IRENA (2024a). *Critical Materials. Batteries for Electric Vehicles*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Critical_materials_Batteries_for_EVs_2024.pdf.
13 IEA (2025c). How can innovation help secure future battery markets and mineral supplies? International Energy Agency. Available at: https://www.iea.org/commentaries/how-can-innovation-help-secure-future-battery-markets-and-mineral-supplies.
14 Sustainable Truck&Van (2024). Almost 65,000 zero-emission trucks and tractor-trailers were sold in China in the first half of 2024, ICCT says. Available at: https://www.sustainabletruckvan.com/icct-report-china-truck-sales-h1-2024

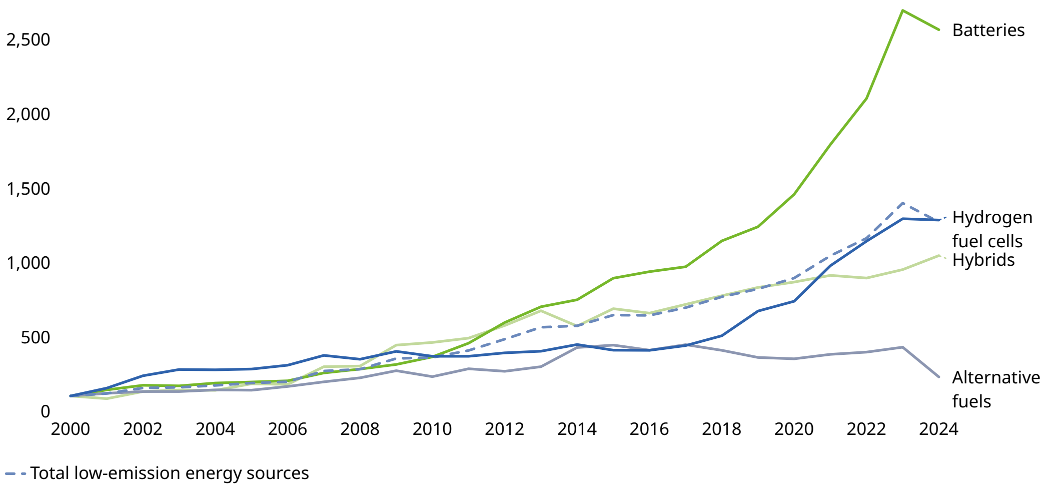
Patenting growth compared to other technologies

When we compare the development of patenting activity in the four key low-emission energy sources (batteries, hydrogen fuel cells, hybrids, alternative fuels) for heavy-duty road vehicles with both the overall patenting trends in heavy-duty road transport and total global patenting, it becomes clear that innovation speed in low-emission energy sources has been very dynamic (Figure 3.4).

While the number of published patent families across all areas of heavy-duty road transport has almost quadrupled since 2000 (compared with a roughly threefold increase in total patents), the number of patents in the four key low-emission energy sources for heavy-duty road vehicles has increased by almost 1,200% – roughly a 13-fold rise. As previously mentioned, the most significant growth was demonstrated by battery-electric heavy-duty road vehicles (+2,500%).

Patenting activity in low-emission energy sources for heavy-duty road vehicles has increased much more than in other technological areas

Figure 3.4 Indexed development of global published patent families in each of the low-emission energy sources for heavy-duty road transport, indexed by earliest publication year, 2000–2024



Note: Indexed development is based on all patent families in the year 2000 being normalized to 100. Total low-emission energy sources refer to the sum of published patent families in batteries, hydrogen fuel cells, hybrids and alternative fuels for heavy-duty road transport.

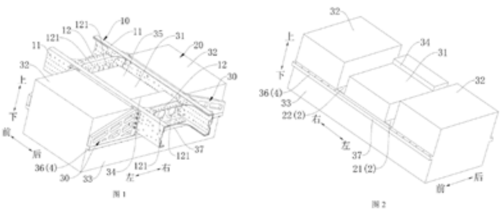
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent spotlight

A recent BYD patent publication relates to a redesigned battery pack with a top cable outlet and recessed groove that improves space utilization and wire routing in electric trucks.

- Patent publication number: **WO 2024/152619 A1**
- Owner: **BYD**
- Title: **Battery pack, chassis assembly and vehicle**
- Publication date: **July 25, 2024**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2024152619).

AI simulation

Source: AI-generated by WIPO.

Problem: The outlet openings of the new energy heavy-duty truck battery pack are located on both sides of the chassis frame, resulting in restricted space for connecting the wire harness and creating difficulties in arranging the battery pack lead wire harness and connecting it to other components.

Solution: Design a battery pack with a groove structure that accommodates the frame longitudinal beam, and forms a cable outlet at the top for the outlet of the battery pack wire harness to facilitate arrangement and connection and improve space utilization.

Benefit: Use of the top outlet makes it convenient to arrange and connect the battery pack wire harness, makes full use of the space above the battery pack, improves the overall space utilization, and improves the structural strength and installation efficiency of the frame.[15]

Jens Hügel, Senior Adviser, International Road Transport Union (IRU)

How do we move on from diesel?

Today's transport operations reflect optimization around a single technology. Moving from diesel to more sustainable options will likely change transportation patterns. Multiple energy sources may coexist to replace diesel in the long run, keeping future operations similar to what stakeholders use today. However, since standardization enables cost reduction and time efficiency, future operations may instead adapt to technology limitations. For instance, cargo owners are exploring a return to owning their own fleets to secure transport capacity while reducing their Scope 3 emissions. While no clear trend has emerged yet, this thinking challenges the decade-long reliance on transport suppliers, who handle over 90% of EU road freight volumes.[16],[17] Another idea under consideration is trailer swapping, where a semi-trailer uses different tractors during its journey. These are just two examples of the many options being explored by shippers and carriers. Once transportation patterns shift to overcome one technology's limitations, it may become even harder for new technologies to penetrate the market without disrupting TCO and flexibility.

15 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.
16 Eurostat (2026). Road freight transport by type of operation and type of transport – Annual data. Available at: https://ec.europa.eu/eurostat/databrowser/view/road_go_ta_tott/default/table?lang=en&category=road.road_go.road_go_tot
17 IRU (2026a). A breakdown of the latest EU road freight volumes and forecast to 2030. International Road Transport Union. Available at: https://www.iru.org/intelligence/road-transport-intelligence/breakdown-latest-eu-road-freight-volumes-and-forecast-2030.

Top inventor locations

China is at the forefront of global patenting activity in low-emission energy sources for heavy-duty vehicles (Figure 3.5). Between 2000 and 2024, China was responsible for almost 17,400 published patent families, based on inventor addresses on published patents. However, it is noteworthy that only 10% of all Chinese patents belong to international patent families with protection extended to two or more countries. This percentage is lower than in all other leading countries. The huge domestic market in China means that many Chinese companies do focus solely on their domestic market and therefore only seek patent protection there. As a result, their inventions are legally protected only within China, which can limit the companies' ability to expand internationally.

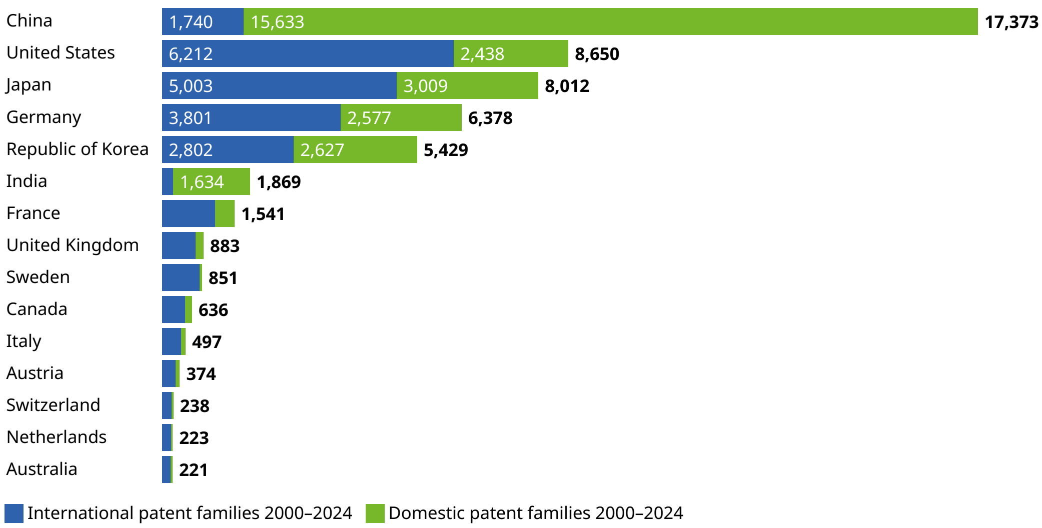
The United States is the second most important research location for low-emission energy sources, with a total of around 8,650 patent families between 2000 and 2024, of which more than 6,200 are international patent families (a 72% share). Japan, Germany and the Republic of Korea are also key research locations, with all three ranking in the top five countries worldwide (third, fourth and fifth, respectively). It is evident that these five locations are responsible for most of the patenting activity related to low-emission energy sources for heavy-duty vehicles, contributing around 89% of the dataset.

Due to its high patent growth rates in recent years, India has propelled itself into sixth place in the ranking, with almost 1,900 patent families. It is interesting to note that India displays a comparable trend to China, with a very high proportion of domestic-only patent families and a share of international patent families of just 1%. As with China, the substantial Indian domestic market is probably a contributing factor in this regard.

India has demonstrated particularly high patenting activity and growth in battery-electric propulsion. For example, India has recently witnessed a surge in the deployment of electric buses: in 2024 alone, roughly 3,600 electric buses were newly registered.[18] As a result, electric buses accounted for around 6.2% of India's overall bus registrations that year, with funding available for the purchase of e-buses and e-trucks on the condition that both vehicle types must be manufactured in India and use domestically assembled batteries.[19]

China is ahead in terms of all published patent families, but the United States, Japan, Germany and the Republic of Korea have more international patent families, suggesting differing patent strategies

Figure 3.5 Total published patent families for the top inventor locations in low-emission energy sources for heavy-duty road transport, 2000–2024



Note: International patent families represent inventions that are protected in multiple jurisdictions.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

18 Daly, C. (2025). India registered thousands of electric buses in 2024. electrive.com. Available at: https://www.electrive.com/2025/03/26/india-registered-thousands-of-electric-buses-in-2024.

19 Ministry of Heavy Industries, Government of India (n.d.). PM E-drive: PM electric drive revolution in innovative vehicle enhancement. Available at: https://pmedrive.heavyindustries.gov.in.

Patent growth and specialization

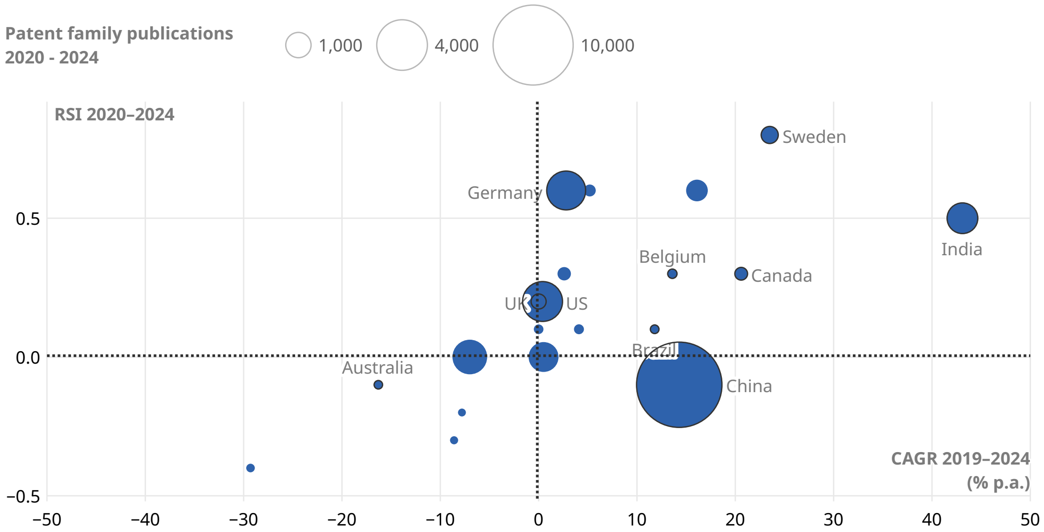
Since 2000, China has experienced the highest patent growth rates of any of the top 15 inventor locations. Between 2000 and 2019, Chinese patent families expanded by compound rate of 38% per year. However, China's patent growth has slowed in recent years, leading to an annual growth rate of 14% between 2019 and 2024 (Figure 3.6). As the absolute volume of patents has grown significantly, percentage-based growth has naturally levelled off. Meanwhile, rising overcapacity in China's battery production has probably further dampened growth recently, with companies prioritizing cost reduction and efficiency over research and development activities.

Consequently, since 2019, India, Sweden, Canada and France have surpassed China's patent growth rates, albeit from a much lower starting point. In contrast, the annual patenting activity has only increased moderately since 2019 in Germany, has stagnated in the United States and the Republic of Korea, and has even declined in Japan.

As shown in Figure 3.6, it is also noteworthy that China's level of specialization, as measured by the Relative Specialization Index (RSI),[20] is below most other top research locations in the field of low-emission energy sources for heavy-duty road transport. Sweden and Germany demonstrate the highest level of specialization in this field, reflecting a strong emphasis on innovation. These findings align with the advanced truck industries of these countries, which include globally renowned companies such as Mercedes-Benz, Daimler Truck, VW (Scania, MAN), Bosch and Volvo.

China leads in the number of inventions, but patent growth has recently been faster in India, Sweden, Canada and France, with Germany and Sweden showing the strongest specialization

Figure 3.6 Top inventor locations in low-emission energy sources for heavy-duty road transport, by number of published patent families (2020–2024), Relative Specialization Index (2020–2024) and compound annual growth rate, 2019–2024 (% p.a.)



Note: Circle size is proportional to the number of published patent families. The Relative Specialization Index (RSI) is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. The value of 1 indicates the maximum specialization, while the minimum value of –1 indicates zero specialization. An average global specialization level is indicated by a value of 0. The compound annual growth rate (CAGR) measures the average annual patent growth between 2019 and 2024 in percentages.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

20 The RSI compares patenting activity in two or more locations within the same technology area. RSI is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. In other words, RSI has the advantage of providing a comparison of two locations' patenting activity in a technology relative to those locations' overall patenting activity. The effect of this is to highlight locations that have a greater specialism in the technology area studied than would be expected from their overall level of patenting.

Relative specialization in the four low-emission energy sources

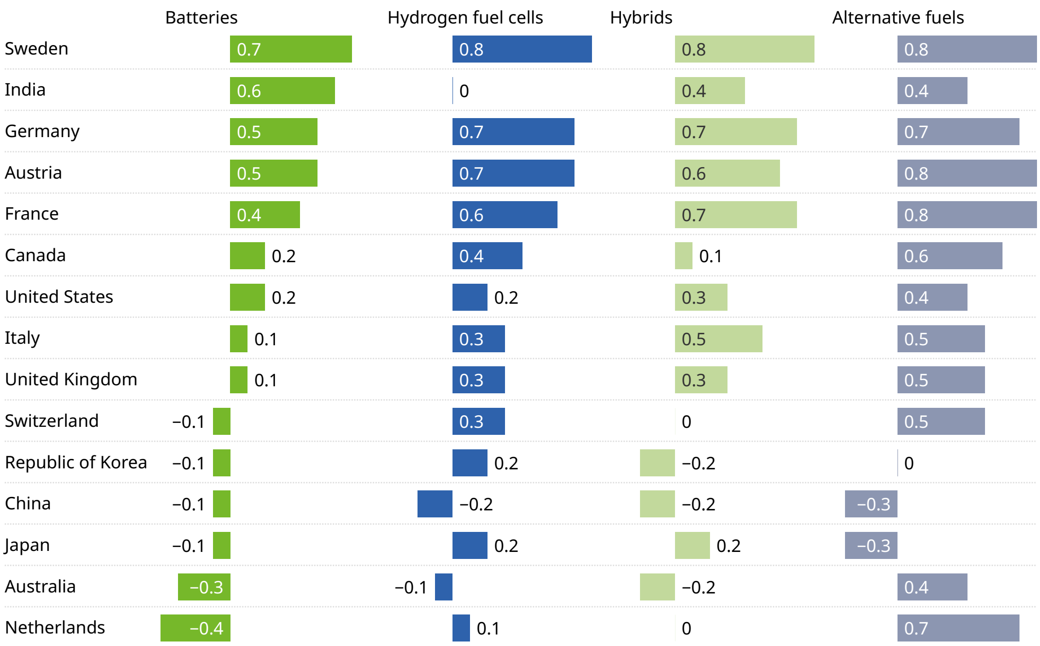
A closer look at the level of specialization across the four low-emission energy source types (Figure 3.7) shows that the most specialized countries (Sweden, Germany, Austria and France) mainly have a high level of specialization across all four types. India is an exception, with high RSI levels in batteries, hybrids and alternative fuels, but only an average RSI in hydrogen fuel cells.

China shows below-average relative specialization across all four energy source types (RSI below 0). It should be noted that low RSI figures do not necessarily indicate low patent volumes. Rather, they suggest that China is less focused on those technologies relative to its overall innovation output. Despite its position as the global leader in terms of patent volume, China exhibits an RSI level that is below the average benchmark.

It is possible to observe different specialization strategies in other countries. For instance, the Netherlands has a high level of relative specialization in alternative fuels, while its specialization in the other energy sources is significantly lower. Some commentators note that the Netherlands is currently facing obstacles to fast expansion of its electric production and distribution grid,[21] which is limiting deployment of electric charging infrastructure.[22] Japan has a moderate above-average level of specialization in hydrogen fuel cells and hybrid vehicles, but comparatively less specialization in batteries and alternative fuels, most probably because the electric emission factor is quite high and feedstock for biofuels limited.[23],[24]

Sweden, Germany, Austria and France have a high level of specialization across all four low-emission energy sources

Figure 3.7 Relative Specialization Index (RSI) in the different low-emission energy sources for heavy-duty road transport for the top inventor locations, 2020–2024



Notes: RSI is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. The value of 1 indicates the maximum specialization, while the minimum value of –1 indicates zero specialization. An average global specialization level is indicated by a value of 0.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

21 IEA (2025b). Grid congestion is posing challenges for energy security and transitions. International Energy Agency. Available at: https://www.iea.org/commentaries/grid-congestion-is-posing-challenges-for-energy-security-and-transitions.
22 ABN AMRO (2025). ESG Economist – Dutch balancing challenge in the renewable era. Available at: https://www.abnamro.com/research/en/our-research/esg-economist-dutch-balancing-challenge-in-the-renewable-era.
23 Ember (2026). Lifecycle carbon intensity of electricity generation. Available at: https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=line&country=FRA~EU-27~OWID_WRL~CHN~JPN~EU+%28Ember%29
24 ICF (2024). Charting the path: SAF Ecosystem in Japan. Available at: https://www.icf.com/insights/aviation/saf-ecosystem-in-japan.

Research priorities

Examining the various research areas of focus across the top research locations (Figure 3.8) reveals noteworthy differences. China has a strong focus on batteries, accounting for 56% of published patent families between 2000 and 2024, boosted by the presence of major battery manufacturers such as CATL and BYD. India (with a battery share of 64%) and the Republic of Korea (47%) are the other two countries that clearly focus on battery research in heavy-duty road transport.

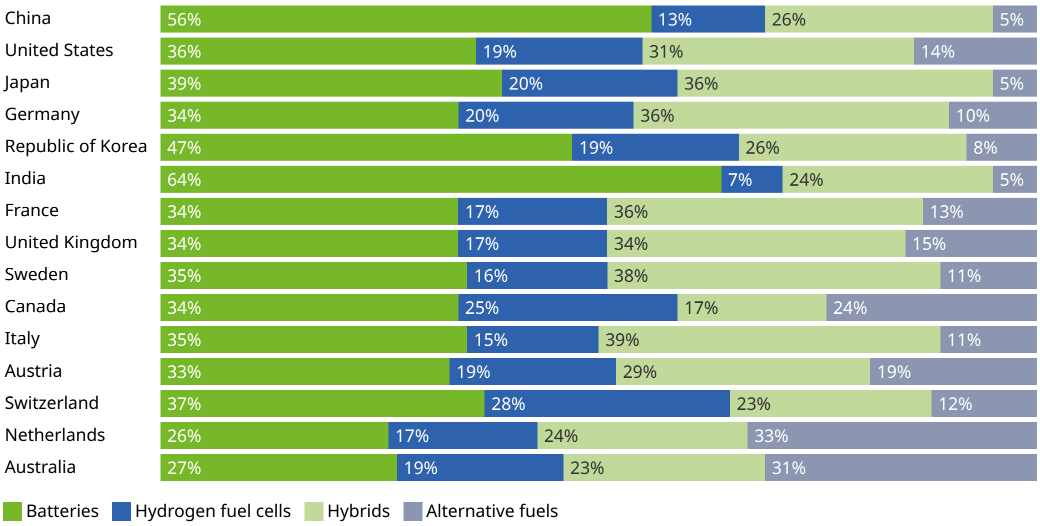
In contrast, Italy and Sweden have the highest share of patent families related to hybrids (39% and 38%, respectively). However, it should be noted that Figure 3.8 is based on data from 2000 to 2024. If data solely from 2024 were considered, the battery share would exceed the hybrid share both in Italy and in Sweden, as well as in all other major research countries. Some commentators note that current local regulations and a vehicle's CO_2 assessment mean that hybrid technology is not beneficial for original equipment manufacturers (OEMs) attempting to meet their decarbonization objectives.[25]

Regarding hydrogen fuel cells in heavy-duty road transport, Switzerland and Canada have the highest shares with 28% and 25% of patenting activity, respectively, while India's share is only 7%.

The Netherlands (33% share) and Australia (31%) have an above-average focus on developing alternative fuels for heavy-duty vehicles. In contrast, Japan and China have a relatively low level of specialization in this field, with shares of 5% each, despite having developed a significant number of patents in absolute terms.

Battery-electric propulsion is the clear research priority in China, India and the Republic of Korea

Figure 3.8 Research priorities in low-emission energy sources for heavy-duty road transport for the top inventor locations, by share based on published patent families, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

The differences in research priorities are also reflected in the location rankings for the four low-emission energy sources (Figure 3.9). China is the clear leader in battery research, with 11,360 patent families, compared to around 3,800 each in, respectively, second- and third-ranked Japan and the United States.

25 European Union (2017). Commission Regulation (EU) 2017/2400. Publications Office of the European Union. Available at: https://eur-lex.europa.eu/eli/reg/2017/2400/oj/eng.

China is also ahead in hydrogen patent families (around 2,650 patent families), but its lead over Japan (1,926) and the United States (1,911) is smaller. In hybrid research, China leads with around 5,250 patent families, with Japan (3,507) and the United States (3,231) behind. In the field of alternative fuels, the United States tops the rankings with almost 1,500 patent families, ahead of China (936) and Germany (752).

China is ahead in batteries, hydrogen and hybrids, while the United States leads in alternative fuels

Figure 3.9 Research priorities in low-emission energy sources for heavy-duty road transport for the top inventor locations, by number of published patent families, 2000–2024

	Batteries	Hydrogen fuel cells	Hybrids	Alternative fuels
China	11,360	2,654	5,252	936
Japan	3,793	1,926	3,507	469
United States	3,773	1,911	3,231	1,472
Republic of Korea	3,172	1,308	1,714	516
Germany	2,574	1,469	2,739	752
India	1,331	139	503	101
France	617	315	657	238
Sweden	371	173	411	117
United Kingdom	360	178	356	158
Canada	265	191	130	184
Italy	205	89	226	63
Austria	153	85	134	85
Switzerland	102	77	64	35
Australia	68	47	59	79
Netherlands	61	41	57	80

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Key filing jurisdictions

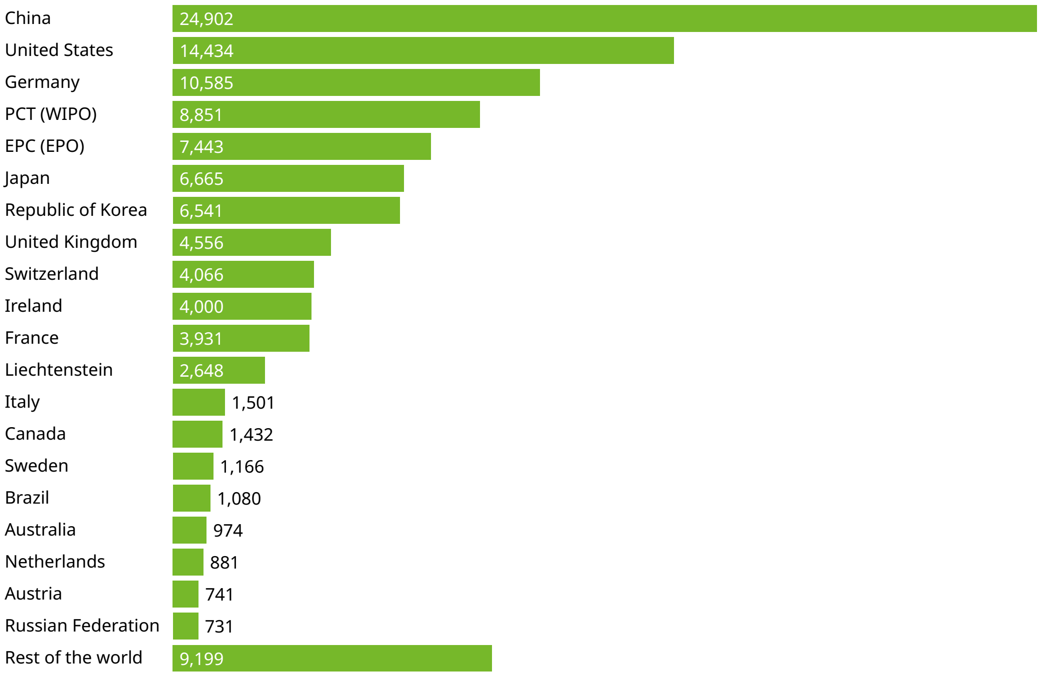
An analysis based on filing jurisdictions of patent families for low-emission energy sources for heavy-duty vehicles provides an additional perspective showing where in the world patent protection is sought. Members of patent families can be filed directly in one or more countries or via the Patent Cooperation Treaty (PCT) or the European Patent Convention (EPC) routes, which are administered by WIPO and the European Patent Office (EPO), respectively. Direct national filings are generally the most cost-effective option when protection is needed in a single market, but they offer little flexibility to expand coverage later if strategic priorities change. In contrast, the PCT system has higher upfront costs but preserves the option to pursue protection in multiple locations and defers major national-stage costs for up to 30 months, giving companies valuable time to evaluate market potential before committing. The EPC route enables a single examination for patent protection across Europe, but total costs depend on how many member states are ultimately validated.

As shown in Figure 3.10, China is not only the leading inventor location in terms of patent families, but also the top country in terms of patent filings. Between 2000 and 2024, over 24,900 patents were filed in China to seek patent protection. In the United States and Germany, the corresponding figures were 14,434 and 10,585, respectively.

The PCT and the EPC are both relevant routes for seeking patent protection. Since 2000, more than 8,850 patent filings have been made under the PCT and almost 7,500 patent filings under the EPC.

China is not only the leading inventor location in terms of low-emission energy sources, but also the top jurisdiction for patent filings

Figure 3.10 Top patent filing jurisdictions in low-emission energy sources for heavy-duty road transport based on the number of published patent families, 2000–2024



Notes: Patent filing jurisdiction refers to the authority in which at least one member of a patent family has been filed. EPC is the European Patent Convention, EPO is the European Patent Office, PCT is the Patent Cooperation Treaty, WIPO is the World Intellectual Property Organization.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Top patent owners

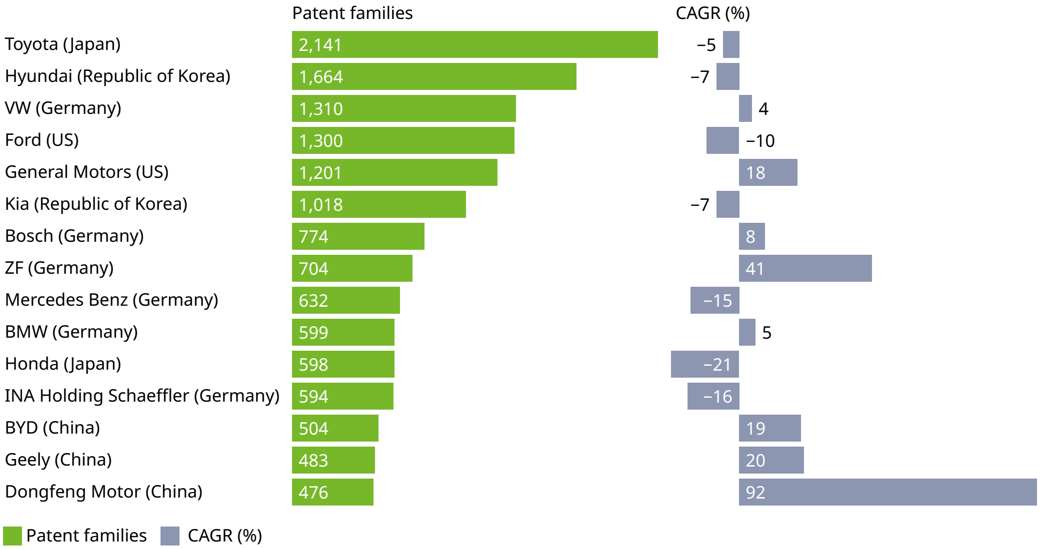
Most leading research entities in the field of low-emission energy sources for heavy-duty vehicles are headquartered in the United States, Japan, Germany, China or the Republic of Korea (Figure 3.11). Within the top 10 patent holders, German automotive manufacturers and suppliers account for five positions: VW (owner of Traton (Scania and MAN brands)), Bosch, ZF, Mercedes-Benz and BMW. The United States is represented by Ford and General Motors (GM), while the Republic of Korea's leading firms, Hyundai and Kia, also rank among the top 10. Japan's involvement is evident through Toyota, which owns Hino Motors and Daihatsu. The first Chinese companies to appear in the global patent ranking are BYD (13th) and Geely (14th). Beyond these, only Volvo from Sweden and Stellantis, headquartered in the Netherlands, feature among the top 25, making them the sole firms outside the five dominant innovation regions.

Notably, the ranking is expected to shift in 2026, following the announced integration of Hino Motors (a Toyota subsidiary) and Mitsubishi Fuso (a Daimler Truck subsidiary) into a new independent company, ARCHION, which is scheduled to begin operations in April 2026.[26]

26 Daimler Truck (2025). Daimler Truck affiliate Mitsubishi Fuso and Hino Motors with updates on the integration. Available at: https://www.daimlertruck.com/en/newsroom/pressrelease/daimler-truck-affiliate-mitsubishi-fuso-and-hino-motors-with-updates-on-the-integration-53230624.

Toyota clearly leads the patent race in low-emission energy sources for heavy-duty vehicles, but German strength is evident within the top 10 patent owners

Figure 3.11 Top patent owners in low-emission energy sources for heavy-duty road transport, by number of published patent families, 2000–2024, and their annual patent publication growth rate, 2019–2024



Note: The compound annual growth rate (CAGR) measures the average annual patent growth between 2019 and 2024 in percentages.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Toyota is currently leading the way in the patent race for low-emission energy sources for heavy-duty vehicles, having published almost 2,150 patent families since 2000. This is significantly ahead of second-placed Hyundai Motor, which has published 1,664 patent families. Toyota has published the most patent families in three of the four low-emission energy sources (batteries, hydrogen fuel cells and hybrids) and ranks eighth in alternative fuels. Toyota's wide-ranging innovation capabilities are closely linked to its strategic emphasis on both electric and hydrogen fuel cell vehicles.[27] The company's strategy for battery production involves a combination of in-house production, joint ventures and external suppliers. In addition, Toyota continues to work on fuel cell heavy-duty vehicles. For instance, Toyota is working in partnership with Isuzu to develop next-generation fuel cell buses.[28]

Hyundai's strategy is comparable to that of Toyota, with large investments in hydrogen and battery-electric heavy-duty vehicles. This includes the recent introduction of the XCIENT Fuel Cell truck[29] and of electric commercial vehicles in partnership with IVECO.[30] Other companies, such as BYD, are concentrating their research efforts on battery-powered heavy-duty vehicles.

It is interesting to note that there are no universities or research institutions among the top 25 patent publishers. This signals that heavy-duty road transport is a mature industry where research is dominated by corporate research and development activities, particularly for applied technologies like batteries, fuel cells or hybrid drivetrains. While universities and public research institutions do not appear among the top 25, they nonetheless contribute to fundamental research and early-stage development.

27 WIPO (2025). *WIPO Technology Trends Report 2025: The Future of Transportation*. World Intellectual Property Organization. Available at: https://www.wipo.int/web-publications/wipo-technology-trends-future-of-transportation/en/index.html.
28 Toyota (2025). Isuzu and Toyota to jointly develop next-generation fuel cell route bus. Available at: https://global.toyota/en/newsroom/corporate/43355086.html.
29 Hyundai (2025). Hyundai Motor unveils the new XCIENT heavy-duty fuel cell truck at ACT Expo 2025. Available at: https://www.hyundai.com/worldwide/en/newsroom/detail/hyundai-motor-unveils-the-new-xcient-heavy-duty-fuel-cell-truck-at-act-expo-2025-0000000949.
30 Hyundai (2024). Hyundai Motor Company and IVECO charge ahead with revolutionary electric commercial vehicle at IAA Transportation 2024. Available at: https://www.hyundai.news/eu/articles/press-releases/hyundai-motor-company-and-iveco-charge-ahead-with-revolutionary-electric-commercial-vehicle.html.

Tsinghua University in China is the first university on the list (ranked 51st), having published 131 patent families since 2000. The Zero Carbon Transportation Research Center at Tsinghua University has four key research areas: electrochemical power, battery and energy storage systems; hydrogen fuel cells and electrolytic green hydrogen systems; vehicle-to-grid (V2G) and intelligent energy systems; zero-carbon engines and intelligent powertrains.[31]

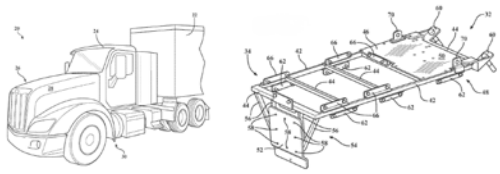
There are also currently no Indian companies in the top 25. Tata Motors is the first Indian company in the ranking, coming in at 30th place with 234 published patent families and significant patent growth in recent years. This trend may change in the future because Tata Motors has recently purchased European OEM IVECO.[32]

Patent spotlight

A granted Toyota Motor patent covers a modular carrier assembly enabling multiple fuel cell stacks to be installed or removed as a single unit in heavy-duty vehicles.

- Patent publication number: **US 11845346 B2**
- Owner: **Toyota Motor**
- Title: **Carrier assembly for multiple fuel cells**
- Publication date: **August 11, 2022**
- Grant date: **December 19, 2023**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=US370958484).

AI simulation

Source: AI-generated by WIPO.

Problem: Heavy duty trucks require multiple fuel cell stacks to meet increased power and load requirements, necessitating an efficient assembly and removal system for improved serviceability.

Solution: A powertrain carrier assembly with a frame structure and mounting system that allows for the secure installation and removal of multiple fuel cell assemblies as a single unit, utilizing a three-point mounting system and high-strength steel components, suitable for both new and retrofitted vehicles.

Benefit: Enables efficient assembly and removal of multiple fuel cell assemblies, enhancing serviceability and build efficiency with high repeatability, while accommodating different fuel cell designs and power outputs.[33]

Patent growth

There has been a significant increase in the number of patents related to low-emission energy sources for heavy-duty vehicles in recent decades. However, there has been a slight slowdown in patent growth since 2019, as shown in Figure 3.11. This is reflected in the patent dynamics of

31 Tsinghua University (2024). Zero Carbon Transportation Research Center. Available at: https://www.icon.tsinghua.edu.cn/en/info/1060/1050.htm.
32 Iveco Group (2025). Tata Motors to acquire Iveco Group, together creating a global player in commercial vehicles. Available at: https://www.ivecogroup.com/media/corporate_press_releases/2025/july/tata_motors_to_acquire_iveco_group_together_creating_a_global_player_in_commercial_vehicles.
33 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

the top patent owners. Between 2019 and 2024, only 14 out of 25 of the top patent owners have increased their published patent families, with particularly strong growth from Dongfeng Motor, Chery Holding Group, ZF and Volvo. Dongfeng Motor has made substantial investments in recent years in the development of battery-electric, hybrid and hydrogen fuel cell heavy-duty vehicles.[34]

In contrast, over the past five years, 11 of the leading patent holders have seen a decline in their patent output. Notably, particularly major Japanese companies, such as Denso, Aisin, Honda and Nissan, published a reduced number of patent families in 2024 compared to 2019.

Research priorities

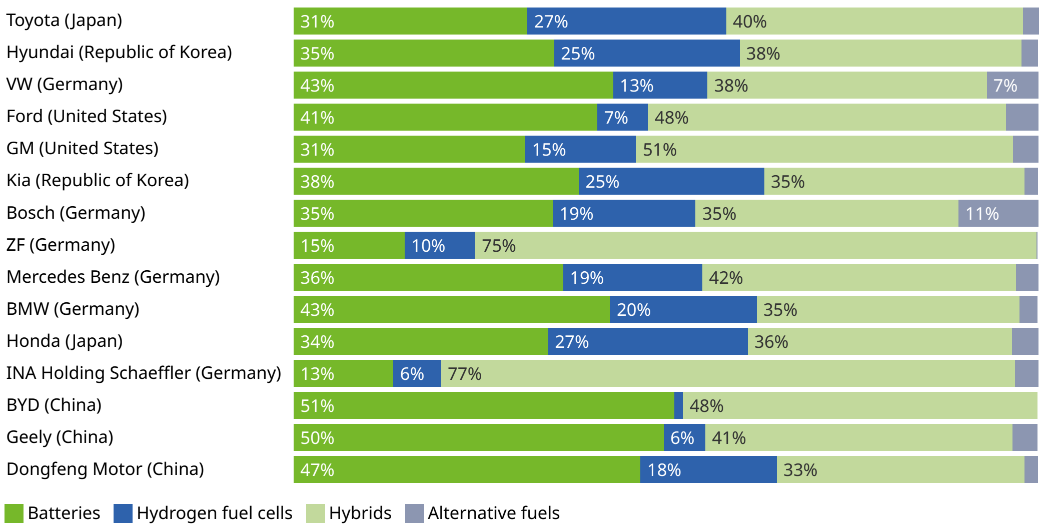
The technological research priorities of the top patent owners within the field of low-emission energy sources for heavy-duty road transport is shown in Figure 3.12. In percentage terms, battery-electric and hybrid patent families represent the most significant segments for the majority of the top patent owners when considering the entire analysis period from 2000 to 2024. It should be noted that battery-electric patenting has been the most dynamic for the majority of companies; consequently, focusing solely on the past five years would result in higher battery-electric shares compared with hybrid shares for most firms.

Key research players, including Toyota, Hyundai, Kia and Bosch, exhibit a similar pattern, with battery- and hybrid-related patent families accounting for the majority of all low-emission energy source patents since 2000, while hydrogen also represents a notable research focus area.

Other companies, including VW,[35] Ford, BYD and Geely, have only a small share of hydrogen fuel cell patents. Hybrid technologies are particularly important for German automotive suppliers ZF and INA Holding Schaeffler and for the Japanese automotive supplier Aisin. State Grid Corporation of China is an exception in that the company focuses almost exclusively on battery-electric research. Alternative fuels represent a minor aspect of the portfolios of most of the leading patent holders, except for Caterpillar, where alternative fuels account for almost 50% of the company's patent families in the low-emission energy sources sector.

Battery-electric and hybrid heavy-duty vehicles are the most important research areas for the majority of top patent owners

Figure 3.12 Research priorities of the top patent owners in low-emission energy sources for heavy-duty road transport, based on the number of published patent families, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

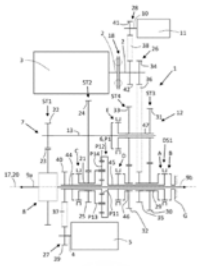
34 Hydrogen Today (2024). Dongfeng ramps up hydrogen research. Available at: https://hydrogentoday.info/en/dongfeng-hydrogen-rd.
35 Traton (2022). Why the battery electric drive represents the future for trucks. Available at: https://traton.com/en/newsroom/current-topics/why-the-battery-electric-drive-represents-the-future-for-trucks.html.

Patent spotlight

A granted patent from ZF describes a compact hybrid transmission integrating combustion and electric drives through a superposition gear system to improve flexibility and installation efficiency.

- Patent publication number: **DE 102021204618 B4**
- Owner: **ZF Friedrichshafen**
- Title: **Hybrid transmission device and motor vehicle with a hybrid transmission device**
- Publication date: **November 10, 2022**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=DE378342232).

AI simulation

Source: AI-generated by WIPO

Problem: Existing hybrid transmission devices for motor vehicles lack a compact and efficient design that effectively integrates both internal combustion engines and electric motors, limiting their flexibility and installation space utilization.

Solution: A hybrid transmission device with a superposition gear system that includes a first and second transmission input shaft for the internal combustion engine and electric motor, respectively, a planetary gear set, countershaft stage and switching elements for electrodynamic and hybridized drives, allowing for a compact and flexible power transmission system.

Benefit: The solution provides a compact design that optimizes installation space, enhances flexibility and enables efficient electrodynamic starting and hybridized driving modes, improving the overall performance and efficiency of the motor vehicle.[36]

Top patent owners in the four low-emission energy sources

The rankings for the top patent owners in battery-electric, hydrogen fuel cell and hybrid heavy-duty vehicles demonstrate notable similarities, with research in all three areas being led by automotive manufacturers and suppliers. However, the top patent owners in alternative fuels are more diverse, with construction vehicles company Caterpillar leading the ranking. The alternative fuels list also includes the industrial gas companies Linde and Air Liquide, the fuel specialist Westport Fuel Systems, the aerospace and defense company Rolls-Royce and the Chinese Academy of Sciences.

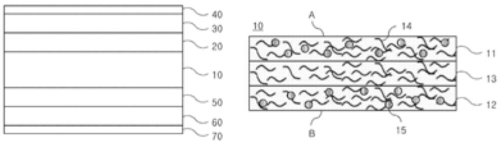
36 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Patent spotlight

Hyundai Motor's recently published patent application describes an all-solid-state battery using a porous composite membrane to improve lithium uniformity, energy density and battery lifespan.

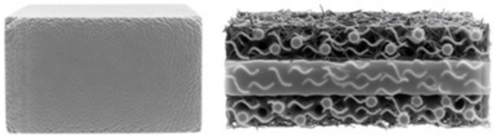
- Patent publication number: **KR 1020240116099 A**
- Owner: **Hyundai Motor**
- Title: **An all-solid-state battery including a porous composite membrane**
- Publication date: **July 29, 2024**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=KR436438098).

AI simulation



Source: AI-generated by WIPO

Problem: Non-cathode all-solid-state batteries exhibit lower energy density, capacity retention issues and a shorter lifespan due to uneven lithium deposition on the current collector, leading to thickness deviations during charging and discharging cycles.

Solution: A non-cathode all-solid-state battery design incorporating a composite membrane with a conductive material, including carbon nanofibers or carbon nanotubes, forming a porous structure that stores lithium ions in pores and uses metal powders to facilitate lithium alloying, with specific layer compositions to enhance stability and capacity.

Benefit: The design achieves high energy density, excellent capacity retention and a long lifespan by storing lithium uniformlywithin the composite membrane, preventing structural collapse and dendrite formation.[37]

37 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

4 Energy infrastructure

This chapter examines the development of energy infrastructure required to support the decarbonization of heavy-duty road transport. It analyzes patent trends in charging networks, smart grids and hydrogen refueling systems, highlighting rapid growth in battery-electric infrastructure, key technological challenges and the countries driving innovation in large-scale energy distribution.

The fundamental constraint

Decarbonizing heavy-duty road transport relies on more than just adopting low-emission energy sources. It is also vital to establish a robust, scalable energy infrastructure backbone. The deployment and operational efficiency of zero-emission trucks and buses is fundamentally constrained by the availability of energy distribution networks. This infrastructure includes high-power charging networks for battery-electric vehicles (BEVs) and grid updates, as well as hydrogen generation, storage, distribution, and refueling stations for fuel cell vehicles (FCEVs). This chapter explores each of these domains and the technical and economic hurdles driving significant global patenting activity.

- Battery-electric heavy-duty vehicles (HDVs) require a widespread and reliable charging infrastructure, ranging from private depot chargers to minimize operating costs, to public high-power stations located along freight transport routes to maintain capacity. Current innovation in this sector is focused on overcoming the time constraints of recharging large battery packs, with the aim of enabling charging times comparable to driver rest breaks. However, the shift to megawatt-scale power transfer introduces significant technical challenges. They include the thermal management of cables and connectors (e.g., liquid cooling), standardizing interoperable interfaces and integrating stations into the power grid.
- Despite the rapid expansion of heavy-duty charging networks in China, Europe and Northern America in recent years, infrastructure deployment lags behind the trajectory required for large-scale fleet electrification. The scale of the investment gap is significant. For instance, the International Council on Clean Transportation (ICCT) estimates that by 2030, the European Union alone will require between 60,000 and 80,000 public chargers, including 4,000 to 5,300 megawatt-scale chargers, alongside 150,000 to 175,000 private depot chargers.[1] This stands in stark contrast to the estimated only 1,500 public heavy-duty chargers in existence in 2025, highlighting the urgent need to accelerate infrastructure rollout.[2]
- Hydrogen-based transport requires the establishment of a dedicated value chain, encompassing the production, storage and transportation of low-carbon hydrogen, as well as the construction of refueling stations. Compared to stations for passenger vehicles, hydrogen refueling stations for heavy-duty vehicles require higher pressure, greater storage capacity and faster dispensing technologies, which increases cost and technical complexity. Furthermore, technical divergence regarding storage methods – specifically between compressed gaseous hydrogen and liquid hydrogen – is driving innovation in station design. Currently, the main barriers to scaling up are the cost and availability of low-carbon hydrogen, whether produced by electrolysis or carbon capture reforming, and the high capital expenditure required for storage and distribution.
- While deployment of hydrogen refueling stations is growing globally, it remains at an early stage. According to the Ludwig-Bölkov-Systemtechnik (LBST) H2stations.org, approximately 1,160 hydrogen refueling stations were operational worldwide at the end of 2024.[3] China leads global deployment, with 384 stations, followed by the Republic of Korea (198), Japan (161), Germany (113) and the United States (89).

Existing infrastructure can be used to distribute alternative fuels

Unlike electric and hydrogen pathways, alternative low-emission fuels – such as advanced biofuels, synthetic fuels (e-fuels) and renewable natural gas – do not require the development of an entirely new infrastructure system. These fuels are for the most part “drop-in” energy carriers that can be blended with, or used as substitutes for, existing liquid fuels or pipeline-grade natural gas.

1 ICCT (2025a). Charging infrastructure needs for battery-electric trucks in the European Union by 2030. International Council on Clean Transportation. Available at: https://theicct.org/publication/charging-needs-battery-electric-trucks-europe-oct25.
2 EAFO (2025). New public HDV recharging infrastructure data now live on EAFO. European Alternative Fuels Observatory. Available at: https://alternative-fuels-observatory.ec.europa.eu/general-information/news/new-public-hdv-recharging-infrastructure-data-now-live-eafo.
3 H2stations.org by LBST (2025). Milestone reached: Over 1,000 hydrogen refuelling stations in operation worldwide in 2024. H2stations.org by Ludwig Bölkow Systemtechnik. Available at: https://www.h2stations.org/press-release-2025-milestone-reached-over-1000-hydrogen-refuelling-stations-in-op-eration-worldwide-in-2024.

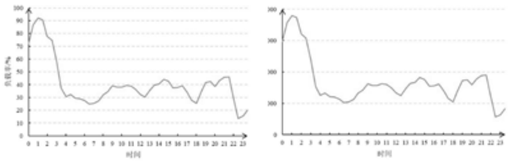
As a result, infrastructure deployment is not the main technological constraint for alternative fuels. The real limitations lie in feedstock availability, production scalability and cost competitiveness. Because the distribution infrastructure –pipelines, storage terminals, tanker trucks, and dispensing pumps – consists of long-established technologies that often need only minor modification, patent activity related to the infrastructure dimension of alternative fuels is limited. Innovation in this area is focused primarily on fuel production technologies rather than on distribution systems. For that reason, this chapter does not provide a patent analysis of alternative fuel infrastructure.

Patent spotlight

A China Southern Power Grid patent application describes an optimized bus charging control method that shifts charging to off-peak periods, reducing grid load and improving power reliability.

- Patent publication number: **CN 115345345 A**
- Owner: **China Southern Power Grid**
- Title: **Bus charging station regulation and control method based on charging pile state optimization**
- Publication date: **November 15, 2022**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=CN379913374)

AI simulation

Source: AI-generated by WIPO

Problem: Existing technology mainly relies on power regulation in electric vehicle charging regulation, which results in high equipment modification requirements and difficulty in effectively balancing the interests of all parties. It is also difficult to transfer peak loads to off-peak periods, affecting the power quality and reliability of the power grid.

Solution: By collecting regional bus station load data and the charging data of individual electric buses, an electric bus dispatching model is and a cluster electric bus charging optimization model is established to optimize the charging period, reduce the peak load at night, and use the double-layer optimization model to realize the transfer of peak load to off-peak hours.

Benefit: Achieves the maximum reduction of feeder load rate, ensures safe charging operation, and achieves significant peak-cutting and valley-filling effects. It has convenient conditions for implementation, reduces feeder load rate, and improves the reliability and economic operation of the power grid.[4]

4 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Global patent development

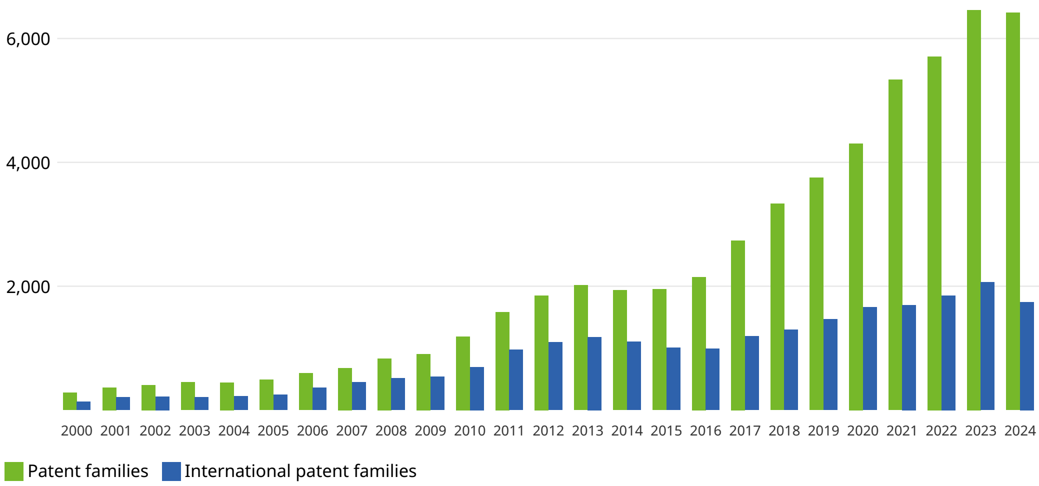
Global patent development in energy infrastructure

Between 2000 and 2024, patents in energy infrastructure for heavy-duty road vehicles – encompassing charging, smart grids and hydrogen solutions – skyrocketed, surging from around 280 to over 6,400 published families (Figure 4.1). International patent families (IPFs) show a similar increase, rising from 136 to almost 1,750. However, despite this overall expansion, 2024 saw the first slight decline in patent publications since 2014. This is primarily due to a slowdown in patenting activity in China following years of significant growth, although decreases are also seen in other leading countries, including the United States, Japan, the Republic of Korea and Germany.

Overall, the trajectory of patenting activity in energy infrastructure closely mirrors that of low-emission energy sources for heavy-duty road transport. Both areas have shown comparable long-term expansion, with compound annual growth rates of 12% for low-emission energy sources and 14% for energy infrastructure over the past 25 years. This parallel development underscores a strong interdependence between innovation in energy technologies and the infrastructure required to support deployment.

Patenting activity for energy infrastructure for heavy-duty road transport has risen dramatically since 2000, mirroring the development in low-emission energy sources

Figure 4.1 Published patent families in energy infrastructure for heavy-duty road transport by earliest publication year, 2000–2024



Note: International patent families represent inventions that are protected in multiple countries.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

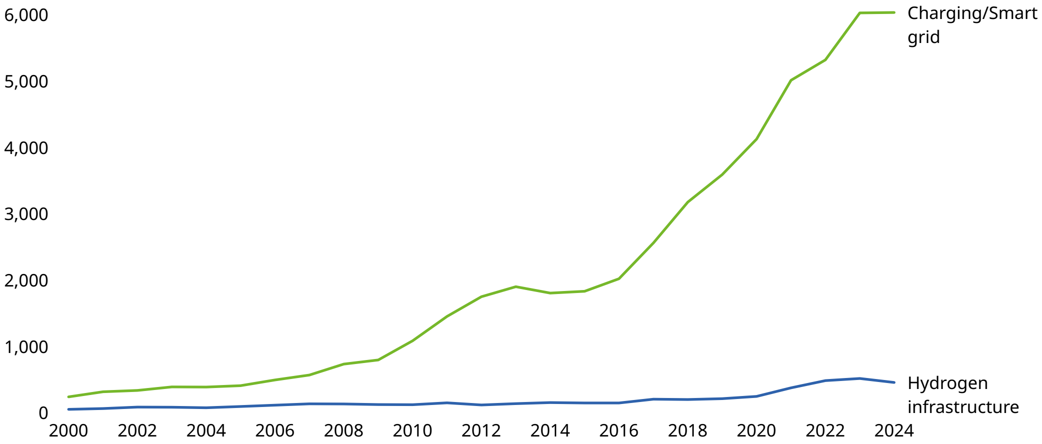
Comparison between battery-electric and hydrogen infrastructure

Taking a closer look at patenting activity reveals that charging infrastructure and smart grid technologies dominate research within the area of energy infrastructure for heavy-duty road transport (Figure 4.2). The number of published patent families in this field increased from 236 in 2000 to 6,028 in 2024. Although hydrogen infrastructure patent activity has also increased dynamically, it remains significantly more modest, rising from 48 family publications in 2000 to 453 in 2024.

This significant disparity reflects the current technological and economic consensus within the heavy-duty vehicle sector. Battery-electric vehicles are favored because of their superior energy efficiency and projected lower total cost of ownership. Such technology is also an opportunity for new business models, with the possibility of offering different charging technologies (plug, wireless) and different energy transfer (grid-to-vehicle, vehicle-to-vehicle and vehicle-to-grid). This strategic preference is driving extensive research and development and patenting into high-power charging standards and complex smart grid integration technologies. Again, development is in line with the findings in Chapter 3 on low-emission energy sources, where batteries are shown to have consistently been the clear focus of research efforts.

Global research activities focus on battery-electric infrastructure

Figure 4.2 Published patent families in each energy infrastructure type for heavy-duty road transport by earliest publication year, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Liquid versus gaseous hydrogen for heavy-duty fuel cell vehicles

The deployment of fuel cell-electric and hydrogen combustion engines in heavy-duty road transport currently faces a strategic choice between gaseous hydrogen and liquid hydrogen infrastructure – one that has significant logistical, technical and economic implications.

Gaseous hydrogen, typically compressed to 350 bar or 700 bar, is the dominant form in today's hydrogen landscape, because gaseous hydrogen refueling stations are easier and cheaper to build. However, gaseous hydrogen has a lower volumetric energy density than liquid hydrogen. This limits range and requires large, heavy high-pressure tanks to be onboard the vehicle. Liquid hydrogen, stored cryogenically at around –253°C, offers a significantly higher volumetric energy density, which is crucial for maximizing range and payload for long-haul trucking. The major drawbacks are the energy-intensive liquefaction process (typically consuming 25–35% of the hydrogen's energy content) and boil-off losses during storage and transport, when some of the hydrogen vaporizes naturally due to heat ingress. Therefore, the transition to LH_2 would require significant investment in liquefaction capacity and new supply chains.

For long-haul trucking, some company and industry forecasts point toward liquid hydrogen being the preferred long-term option.[5] For instance, Daimler Truck and Linde are actively developing liquid hydrogen infrastructure, projecting that its higher storage density, greater range and faster refueling will make it the more cost-effective and scalable solution for long-haul trucking.[6]

On the other hand, there are also current research projects, such as the EU Horizon RHeaDHy project (which includes corporate partners such as Toyota, ENGIE, and Hydrogen Refueling Solutions), focused on developing high flow refueling components and specialized cooling technology for gaseous hydrogen with the goal to allow refueling of 700 bar H2 trucks at 100kg within 10 minutes.[7]

Therefore, while the long-term dominant solution for long-haul trucking remains uncertain, gaseous hydrogen is likely to maintain relevance for shorter or regional transport operations, such as city buses and localized logistics, where its simpler infrastructure retains an advantage.

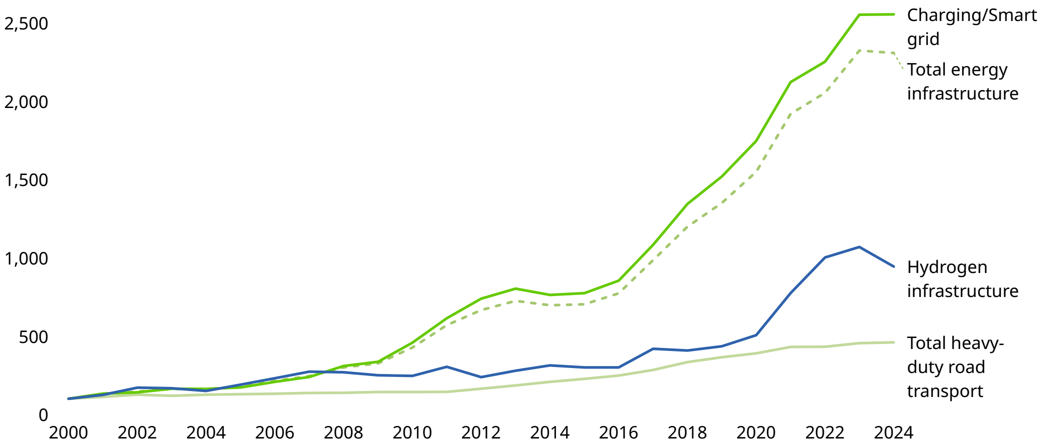
5 Berylls Strategy Advisors (2021). *Trucking on Hydrogen at Crossroads: – Will the Future be Gaseous or Liquid?* Available at: https://www.berylls.com/wp-content/uploads/2021/12/BSA-Studie-Trucking-on-Hydrogen-12-2021-v05.pdf.
6 Daimler Truck (2024). Safe, fast and simple: Daimler Truck and Linde set new standard for liquid hydrogen refueling technology. Available at: https://www.daimlertruck.com/en/newsroom/pressrelease/safe-fast-and-simple-daimler-truck-and-linde-set-new-standard-for-liquid-hydrogen-refueling-technology-52581266.
7 See, Refuelling heavy-duty with very High flow Hydrogen (RHeaDHy, a Horizon Europe project) at: https://rheadhy.eu.

Patenting growth compared to other technologies

The rate of patenting in heavy-duty road vehicle energy infrastructure demonstrates strong growth compared to both the overall patenting trends in heavy-duty road transport and total global patenting (Figure 4.3). While published patent families across all heavy-duty road transport areas show only a moderate increase over the general technological average, the energy infrastructure field has experienced growth exceeding 2,200%. This surge is predominantly attributable to the significant rise in patents related to charging solutions and smart grids. This rise is in line with the battery patent trends set out in Chapter 3 on low-emission energy sources.

Patenting activity in energy infrastructure for heavy-duty road vehicles has increased much more than in other technological areas

Figure 4.3 Indexed development of global published patent families in energy infrastructure for heavy-duty road transport, by publication year 2000–2024



Note: Indexed development is based on all patent families in the year 2000 being normalized to100. Total energy infrastructure refers to the sum of published patent families in charging and smart grid technologies, as well as hydrogen infrastructure for heavy-duty road vehicles.

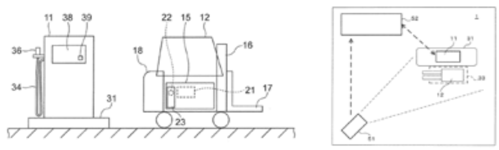
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent spotlight

A granted Toyota patent describes a hydrogen filling system that uses image recognition to identify vehicles and ensure safe, pressure-appropriate hydrogen refueling.

- Patent publication number: **JP 7324652 B2**
- Owner: **Toyota**
- Title: **Hydrogen filling system**
- Publication date: **February 25, 2021**
- Grant date: **August 2, 2023**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=JP319646816)

AI simulation

Source: AI-generated by WIPO.

Problem: Existing hydrogen filling facilities struggle to differentiate between fuel cell vehicles with high and low hydrogen filling pressures, leading to potential erroneous filling due to the absence of communication functions in vehicles with low pressure requirements.

Solution: A hydrogen filling facility equipped with a camera and control device for image recognition to identify the type of vehicle, allowing or prohibiting hydrogen filling based on the vehicle's characteristics, thus ensuring compatibility with the appropriate filling pressure.

Benefit: Prevents erroneous hydrogen filling into vehicles with incompatible pressures by accurately identifying the vehicle type, thereby ensuring safe and correct filling operations.[8]

Deep dive on charging/smart grid technologies

Research activities in the development of charging infrastructure and smart grids for heavy-duty vehicles can be thematically grouped into the following core areas:

Electric vehicle (EV) grid integration technologies are essential for handling the substantial, concentrated power demands of charging depots and public fast-charging systems. These technologies facilitate a two-way flow of energy, enabling fleet batteries to discharge power back to the grid. This helps utilities stabilize the grid and manage peak demand. It also potentially offers a revenue stream for fleet owners. The number of published patent families in this field almost doubled between 2019 and 2024, rising from 648 to 1,244 (Figure 4.4).

Smart grid technologies for heavy-duty road transport share certain themes with EV grid-integration technologies, but also encompass additional areas of research, including digital twins for grid operations and optimization, interoperability standards and communication protocols, and predictive congestion management for electricity networks. In 2024, around 1,000 patent families were published in the field of smart-grid technologies.

Another key research area is charging at site/depot charging, with 891 published patent families in 2024. This area involves stationary infrastructure installed at fleet hubs. It allows operators to leverage cost-effective smart charging protocols overnight to ensure that vehicles are charged using off-peak power in readiness for their daily routes.

8 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Charging point design is the next largest research field, with 685 published patent families in 2024. It encompasses the development and standardization of physical hardware, including high-power connectors and cable management systems, as well as communication protocols. These standards are crucial for ensuring interoperability, allowing any heavy-duty EV to safely and reliably charge at any compatible station. This is an important requirement for the widespread commercial adoption of EVs.

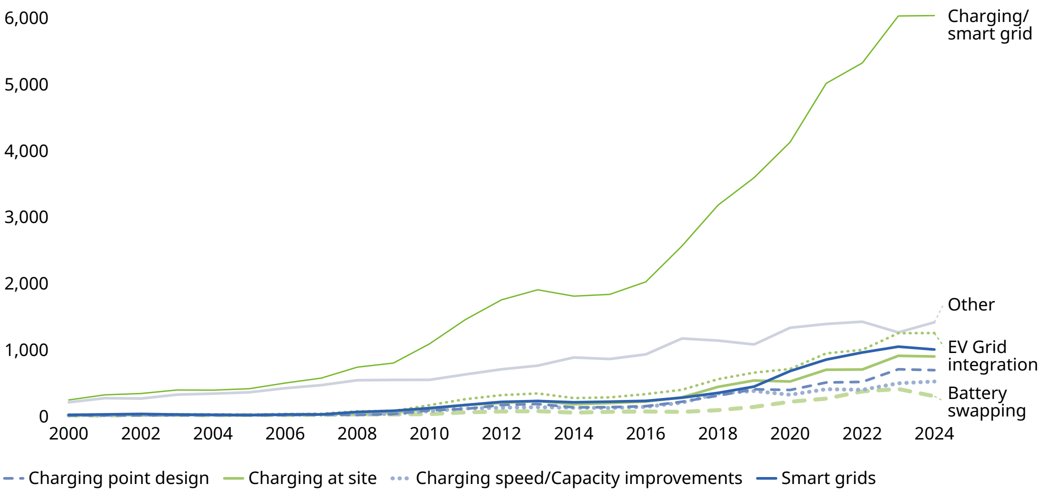
In the field of charging speed and capacity improvement, published patent families rose from 371 to 514 between 2019 and 2024. Research in this area is focused on developing high-power charging systems for large truck batteries. This has led to the development of the Megawatt Charging System (MCS) standard, which is designed to handle a maximum power output of 3.75MW. MCS charging delivers high power output quickly enough to enable long-haul trucks to achieve a significant state of charge during mandatory driver rest stops. The common goal is to enable charging from 20% to 80% battery capacity in under 30 minutes. One such example is Scania's new MCS rapid charging solution.[9] However, technological challenges include grid overload, standardization issues and high costs.[10]

Battery-swapping is a disruptive technology whereby vehicles can exchange a depleted battery pack for a fully charged one in a quick, mechanized process that often takes mere minutes. This avoids charging delays and maximizes vehicle uptime, although it requires highly standardized battery packs. Battery-swapping has gained significant traction in China's heavy-duty road transport sector, as the Chinese government has actively promoted it through subsidies, standardization efforts and inclusion in its development plans.[11] Chinese battery-maker CATL is one of the leaders in battery-swapping technologies and has recently released a new heavy-duty truck battery-swap solution.[12] Published patent families for battery-swapping solutions increased by 17% per year between 2019 and 2024, rising from 131 to 292, this despite a drop in patenting activity in 2024 following a peak in 2023.

A further roughly 1,400 published patent families in 2024 related to battery-electric energy infrastructure could not be clearly assigned to any of the specific categories described above. These patents are shown as "other" in Figure 4.4.

Patenting activity has increased across many different charging and smart grid technologies

Figure 4.4 Global published patent families in the field of different charging solutions and smart grid technologies for heavy-duty road transport, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

9 Scania (2025). Scania launches MCS rapid charging solution at EVS38 – A new era for heavy electric transport. Available at: https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/5072522-scania-launches-mcs-rapid-charging-solution-at-evs38---a-new-era-for-heavy-electric-transport.

10 Bommenahalli, R. and D.R. Chandran (2025). Comparative Analysis of Megawatt Charging Systems Infrastructure for Heavy-Duty Electric Vehicles: North America, Europe, and China. *Journal of Power and Energy Engineering*, 13(10). Available at: https://www.scirp.org/journal/paperinformation?paperid=146565.

11 WEF (2025a). How heavy duty transport can surmount obstacles on their journey to zero. World Economic Forum. Available at: https://www.weforum.org/stories/2025/01/how-heavy-duty-transport-can-surmount-obstacles_on-their-journey-to-net-zero.

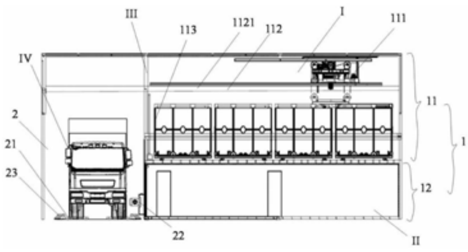
12 CATL (2025). CATL unveils 75# standardized battery swap block, builds "Eight horizontal and ten vertical" battery swap network. Contemporary Amperex Technology. Available at: https://www.catl.com/en/news/6473.html.

Patent spotlight

A Geely patent applicatiocovers a modular heavy truck battery-swap station using stacked containers, reducing construction costs, footprint, and improving swap efficiency and safety.

- Patent publicaion number: **CN 113733969 A**
- Owner: **Geely**
- Title: **Heavy truck battery-swap station**
- Publication date: **December 3, 2021**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=CN345607529)

AI simulation

Source: AI-generated by WIPO.

Problem: Heavy-duty truck battery-swapping stations require a large factory building, have a long construction period, incurhigh costs and it is difficult to solve the problems of short cruising range, long charging time and the high purchase price of pure electric heavy-duty trucks.

Solution: A heavy-duty truck battery-swapping station is designed that adopts a stacked and connected upper and lower container structure. The battery turnover layer is located in the upper container, and the control layer in the lower container. All battery swapping-related equipment is distributed in the two containers. Supports modular design and transportation, and complete overall assembly and debugging before leaving the factory.

Benefit: Realizes a low-cost, small-area power swap station, shortens the station landing period, reduces construction costs, and improves power swap efficiency and safety.[13]

Top inventor locations

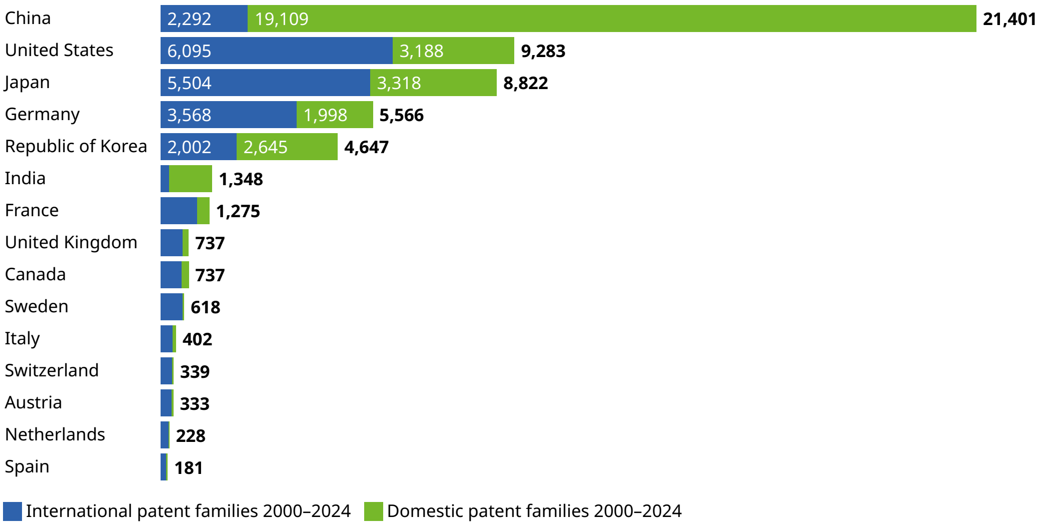
Results for the top inventor locations for energy infrastructure for heavy-duty road transport are very similar to the ones for low-emission energy sources. China is again the key player in global patenting activity for energy infrastructure for heavy-duty vehicles, with a clear focus on the development of domestic patents (Figure 4.5).

The United States ranks as the second most important research location, with a stronger international focus, as represented by the large number of IPFs. Rounding out the top five key research locations worldwide are Japan (third), Germany (fourth) and the Republic of Korea (fifth).

13 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

China is far in front in terms of published patent families in energy infrastructure for heavy-duty road transport

Figure 4.5 Total published patent families for the top inventor locations in energy infrastructure for heavy-duty road transport, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Inventor location analysis for energy infrastructure for heavy-duty road transport also delivers similar results in terms of patent dynamics and specialization compared to the energy sources (Chapter 3). India, Sweden and Canada have the strongest patent momentum, while Sweden, Germany and Austria the most specialized in heavy-duty energy infrastructure technologies.

Patent growth and specialization

Over the past five years, India has shown a remarkable surge in patenting activity related to heavy-duty energy infrastructure, rising from 39 publications in 2019 to 449 in 2024. This corresponds to a compound annual growth rate of more than 60%, making India by far the fastest-growing innovation location in this field.

Sweden and Canada also have strong momentum, recording average annual increases in published patent families of 24% and 22%, respectively. China, which remains the largest patenting country in terms of absolute numbers, has posted an annual growth rate of around 12% since 2019. In contrast, patenting activity in Germany and Japan largely stagnated over the same period.

When measured by the Relative Specialization Index (RSI), Sweden, Austria, and Germany are the countries most specialized in heavy-duty energy infrastructure technologies. In contrast, China's level of specialization is the lowest among the top research locations.

Relative specialization in heavy-duty energy infrastructure

A closer examination of specialization across battery-electric and hydrogen infrastructure reveals that those countries most specialized in battery-electric infrastructure – Sweden, Germany, Austria and Canada – also exhibit a strong specialization in hydrogen infrastructure.

By contrast, India demonstrates a high degree of specialization only in battery-electric infrastructure, with domestic funding programs supporting this development.[14] France and the United Kingdom stand out for having a significantly higher level of specialization in hydrogen infrastructure than in battery-electric infrastructure. China, meanwhile, shows a below-average relative specialization in both these infrastructure areas, with an RSI score below zero.

14 Ministry of Heavy Industries, Government of India (n.d.). PM E-drive: PM electric drive revolution in innovative vehicle enhancement. Available at: https://pmedrive.heavyindustries.gov.in.

Research priorities

Analysis of research focus across the top 15 locations shows that battery-electric energy infrastructure dominates across all regions (Figure 4.6). In every country examined, patent families related to charging and smart grid technologies account for at least 80% of all patent families in the field of heavy-duty road transport energy infrastructure.

China and India display the strongest emphasis on battery-electric infrastructure, with such patents representing 95% of total activity. By contrast, Austria and France have the highest relative focus on hydrogen infrastructure, with shares of 18% and 17%, respectively.

Battery-electric energy infrastructure is the research priority across all major research locations

Figure 4.6 Research priorities in energy infrastructure for heavy-duty road transport for the top inventor locations, by share based on published patent families, 2000–2024

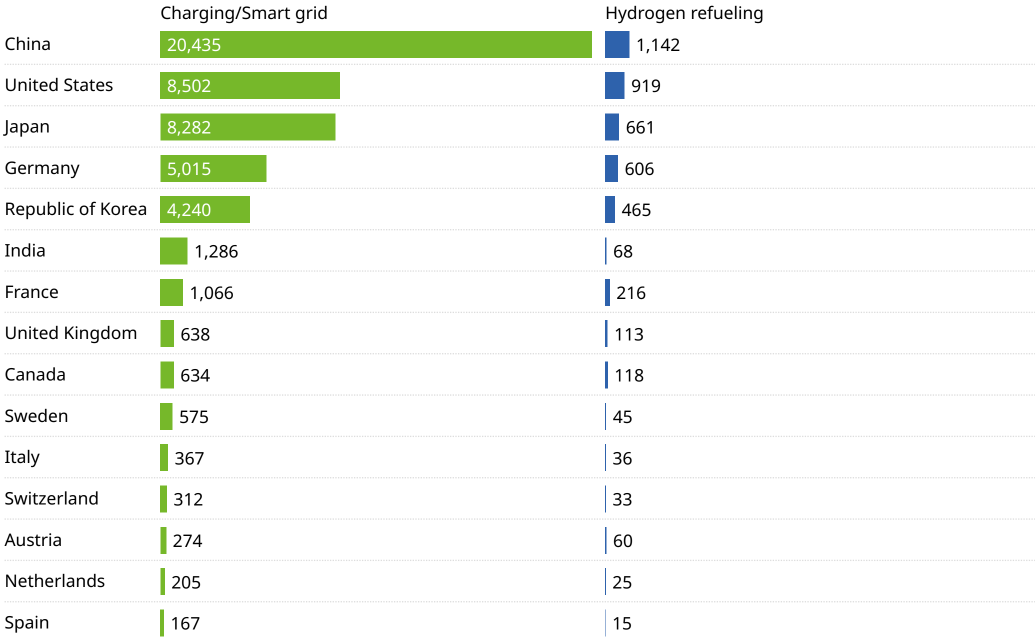
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Differences in research priorities are also reflected in country rankings for the two main types of heavy-duty energy infrastructure (Figure 4.7). China is the undisputed leader in charging and smart grid technologies, with more than 20,400 patent families published since 2000, followed by the United States, with 8,502, and Japan, with 8,282 patent families.

China also leads in hydrogen infrastructure patents, though its advantage over the United States and Japan is less pronounced.

While China dominates battery-electric infrastructure research, competition is closer in the hydrogen infrastructure space

Figure 4.7 Research priorities in energy infrastructure for heavy-duty road transport for the top inventor locations, by number of published patent families, 2000–2024



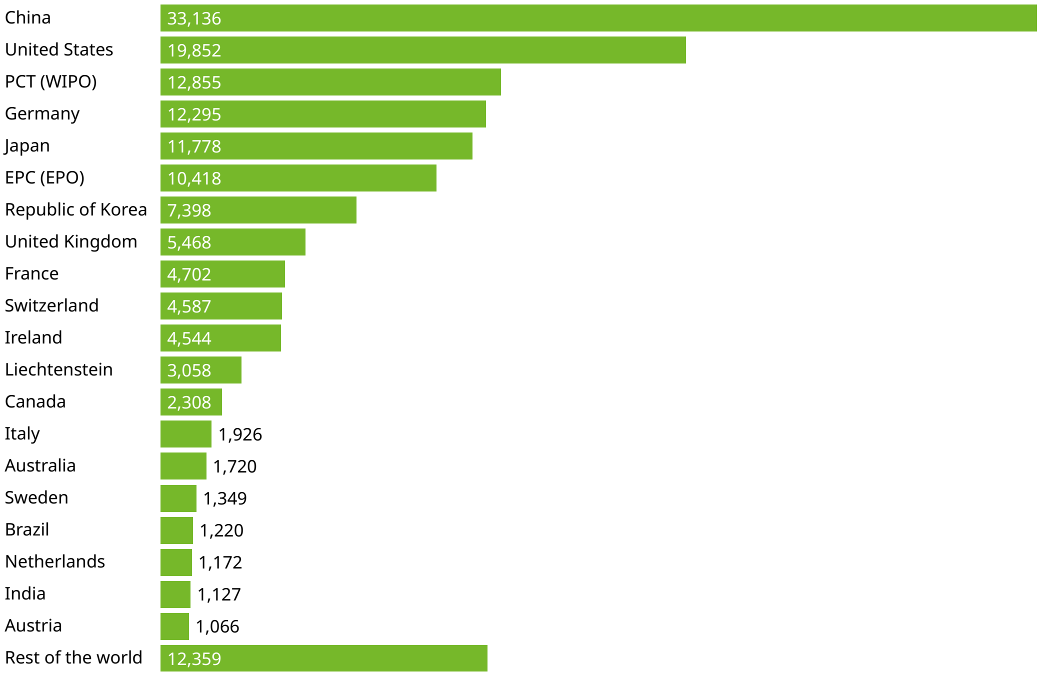
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Key filing jurisdictions

Figure 4.8 shows China is not only the leading inventor location, but also top in terms of patent filings. Between 2000 and 2024, more than 33,100 patents related to heavy-duty energy infrastructure were filed in China. The United States ranks second, with 19,852 filings over the same period. Patent filings under the Patent Cooperation Treaty (PCT) represent the third-largest filing route, with nearly 12,900 applications submitted since 2000.

China is also the top filing jurisdiction for heavy-duty road transport energy infrastructure

Figure 4.8 Top patent filing jurisdictions in energy infrastructure for heavy-duty road transport based on number of published patent families, 2000–2024



Notes: EPC is the European Patent Convention, EPO is the European Patent Office, PCT is the Patent Cooperation Treaty, WIPO is the World Intellectual Property Organization.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Top patent owners

Japan's largest automotive manufacturer, Toyota, heads the list of leading research entities in the field of energy infrastructure for heavy-duty vehicles (Figure 4.9). The company is active in the two core energy infrastructure areas for heavy-duty vehicles – charging/smart grid and hydrogen. For instance, Toyota has recently partnered with Chiyoda Corporation to develop a large-scale electrolysis system to produce green hydrogen.[15]

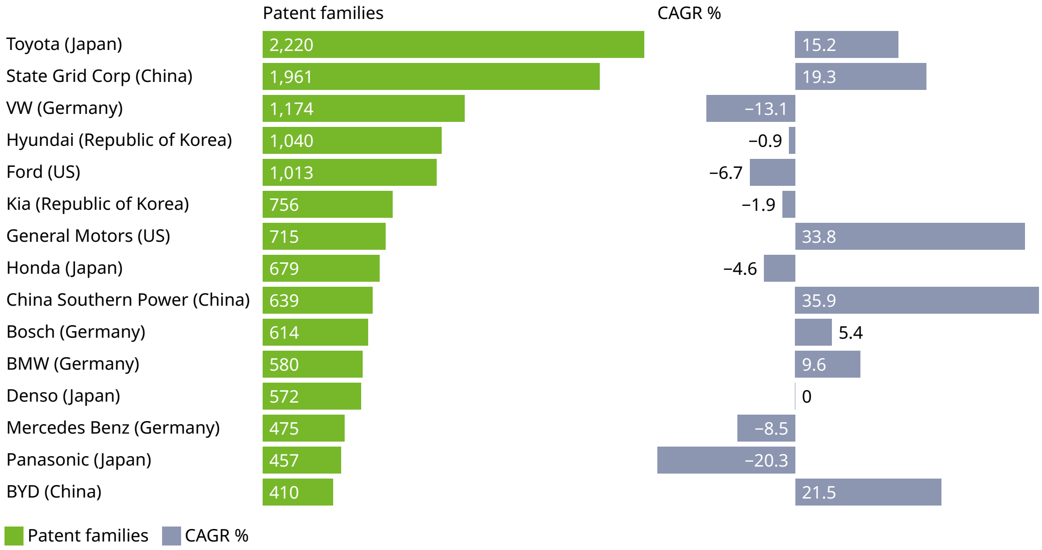
The rest of the top 10 consists mainly of other major automakers and suppliers such as Volkswagen (VW), Hyundai, Ford, Kia, General Motors, Honda, and Bosch. The only non-automotive companies in this top 10 are two Chinese utilities: State Grid and China Southern Power. China's State Grid is developing and testing vehicle-to-grid technologies using electric buses to develop a more flexible and resilient power system.[16]

15 Toyota (2024). Chiyoda Corporation and Toyota jointly developing large-scale electrolysis system. Available at: https://global.toyota/en/newsroom/corporate/40388622.html.

16 PRNewswire (2024). State Grid Jiangsu Electric Power conducts "vehicle-to-grid" interaction test with buses in Zhenjiang. Available at: https://www.prnewswire.com/news-releases/state-grid-jiangsu-electric-power-conducts-vehicle-to-grid-interaction-test-with-buses-in-zhenjiang-302222007.html.

Toyota and State Grid lead the patent race in energy infrastructure for heavy-duty vehicles

Figure 4.9 Top patent owners in energy infrastructure by number of published patent families, 2000–2024, and their annual patent publication growth rate, 2019–2024



Note: CAGR is the compound annual growth rate.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Among the top 25, Volvo (Sweden) and Stellantis, headquartered in the Netherlands, stand out as the only firms outside the five dominant regions (China, Germany, Japan, the United States and the Republic of Korea). Notably, there are no universities or public research institutions in the top 25 – the list consists entirely of corporate actors.

Patent growth

Recent patent trends show that many leading Chinese companies have actively expanded their portfolios in heavy-duty energy infrastructure, with China Southern Power standing out for a compound average annual growth of nearly 36% in published patent families. Among Japanese, European and US companies, growth is more varied: General Motors, Stellantis, and Hitachi show strong increases, whereas Nissan, General Electric (GE) and VW have reduced patenting activity.

Volvo is the company to have recorded the highest growth since 2019, averaging 47% per year. The company participates in the joint venture Milence with Daimler Truck and Traton, targeting the installation of at least 1,700 charging stations across Europe.[17] Volvo is also developing mobile power units for heavy-duty vehicles[18] and charging management systems that enable efficient depot-based charging for commercial fleets.[19]

Research priorities

Battery-electric infrastructure is the main infrastructure research area in terms of patenting activity for all top patent owners in heavy-duty vehicles, accounting for more than 80% of published patent families for the top 25 patent owners. This focus is particularly pronounced among Chinese players like BYD, State Grid, and China Southern Power, whose patent portfolios overwhelmingly concentrate on charging infrastructure and associated grid technologies.

17 Volvo (2024a). How long-range electric trucks can already cover much of today's transport needs. Available at: https://www.volvotrucks.com/en-en/news-stories/insights/articles/2022/nov/long-range-electric-trucks-ready-today.html.
18 Volvo (2025a). Volvo Energy introduces the Volvo PU500 – A reliable power solution for powering any site, anywhere! Available at: https://www.volvoenergy.com/en/news-media/news/2025/apr/volvo-energy-introduces-the-Volvo-pu500.html.
19 Volvo (2024b). Revolutionizing trucking: Volvo's new electric charging service. Available at: https://www.volvoenergy.com/en/news-media/news/2024/aug/volvo-launches-new-service-for-charging-of-electric-trucks.html.

In contrast to the Chinese companies, some European and Japanese automotive companies pursue a more balanced, dual-track approach. BMW has the highest share of hydrogen infrastructure research among major automakers, with nearly 20% of its relevant energy infrastructure patents dedicated to hydrogen infrastructure. While BMW's commercial focus is on the high-end passenger market, it is also a research partner in the heavy-duty sector, using its logistics network to test and advance hydrogen fuel cell technologies for decarbonizing freight transport.[20]

Top patent owners in heavy-duty energy infrastructure

Toyota is the top patent owner both in charging/smart grid technologies and in hydrogen infrastructure. While carmakers and suppliers dominate the ranking in both of the infrastructure categories, some prominent research companies from other industries are also represented. In charging/smart grid technologies, two Chinese utilities, State Grid and China Southern Power, are major players. In hydrogen infrastructure, the three largest global industrial gases companies, Linde, Air Liquide, and Air Products and Chemicals are among the top 15 patent owners.

20 BMW (2025). Moving the future: BMW Group tests Hydrogen Trucks in logistics. Available at: https://www.bmwgroup.com/en/news/general/2025/hydrogen-trucks.html.

5 Vehicle efficiency

This chapter examines technologies that improve the efficiency of heavy-duty road vehicles, focusing on advanced power- and drivetrains, vehicle design and tires, and advanced materials. Patent analysis highlights strong innovation growth led by powertrain technologies, identifies key inventor locations and companies, and shows how vehicle efficiency improvements support the broader decarbonization of heavy-duty road transport.

The drive for greater efficiency

Maximizing vehicle efficiency is a critical, complementary strategy for achieving comprehensive decarbonization of heavy-duty road transport. Efficiency improvements are essential regardless of the energy source (electric, hydrogen, low-carbon fuel-based or hybrid) because they directly reduce the total energy required to transport goods, thereby lowering both operational costs and overall life-cycle greenhouse gas emissions. In the context of new energy vehicles like battery-electric vehicles and fuel cell electric vehicles, higher vehicle efficiency translates directly into a smaller, lighter and less expensive battery or hydrogen storage system, or an extended driving range for a given energy capacity. For vehicles using low-carbon fuels, efficiency minimizes the demand for these often costly and supply-constrained resources.

The drive for greater efficiency in heavy-duty road transport centers on the three main technological pillars detailed below:

- **Electric power- and drivetrains** represent a fundamental shift from mechanical to electrical propulsion, requiring distinct optimizations compared to traditional combustion engines. This category includes the development of e-axles, including electric motors and advanced power electronics, such as inverters that manage energy flow with minimal loss. It also covers specialized gearing for electric vehicles, such as multi-speed transmissions designed to keep electric motors within their optimal efficiency range during the diverse load and speed conditions typical of heavy-duty road transport. While electric motors are inherently efficient, innovations are essential to maximize regenerative braking capability and manage the thermal challenges of high-power continuous operation. Ongoing progress in inverter design, thermal management and power electronics helps to reduce energy losses, extend vehicle range and improve performance in demanding duty cycles.
- **Vehicle design** focuses on minimizing the external forces that resist vehicle movement: aerodynamic drag and rolling resistance. As battery-electric and fuel-cell trucks often carry limited onboard energy compared to diesel tanks, reducing energy waste is paramount. Innovations in this field range from streamlined cab shapes and mirror-replacement camera systems to drag-reducing trailer add-ons. Furthermore, the development of specialized tires is critical; these must balance low rolling resistance to extend range with the durability required to support the increased weight of battery packs and the permanent solicitation of electric motors, which are constantly giving or recovering energy.
- **The use of advanced materials** addresses the challenge of “lightweighting” buses and trucks to offset the substantial mass of zero-emission energy storage systems. Heavy battery packs can significantly reduce a truck’s commercial payload capacity, directly impacting revenue. To update this technology, the industry is researching and developing various lighter-weight materials from high-strength steel to cast aluminum and high-performance materials such as carbon fiber reinforced polymers and ceramics (often used in bearings or thermal management components). These materials offer high strength-to-weight ratios that allow for structural weight reduction without compromising safety or durability. However, widespread adoption of these materials faces challenges due to high manufacturing costs.

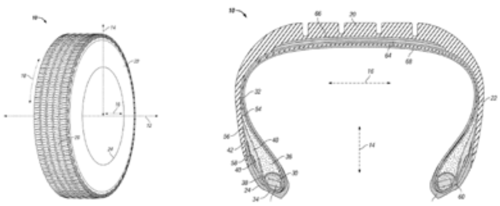
Together, these technological areas form the foundation of a comprehensive efficiency strategy for heavy-duty road transport. Improvements in these technologies reduce total energy demand, lower operating costs, enable smaller batteries or hydrogen storage systems, and ultimately enhance the feasibility and economics of low-emission freight and bus operations. As the sector transitions toward electrification and new vehicle architectures, improvements in drivetrain efficiency, optimized design and advanced materials will become even more critical to meeting climate targets while maintaining performance and competitiveness. This chapter explores the patent landscape across these three intertwined domains, detailing how technological innovation in efficiency is accelerating the practical and economic viability of decarbonized heavy-duty road transport solutions.

Patent spotlight

A Michelin patent application describes a truck tire with a stiff outer bead design that reduces bending hot spots, improves heat resistance and provides enhanced casing durability.

- Patent publication number: **WO 2021/126187 A1**
- Owner: **Michelin**
- Title: **Truck tire with stiff outer bead products**
- Publication date: **June 24, 2021**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2021126187).

AI simulation

Source: AI-generated by WIPO.

Problem: Heavy truck tires are prone to bending hot spots and reduced heat resistance due to flexible bead core designs, which increase manufacturing complexity and cost and do not effectively eliminate bending issues.

Solution: A bead design featuring two bead layers with stiffness of 8–14 MPa, positioned to reduce or eliminate bending hot spots and enhance heat resistance, while avoiding the use of coextruded materials and complex chafer configurations.

Benefit: The design effectively reduces bending hot spots, improves heat resistance, and enhances casing ply fatigue resistance without increasing manufacturing costs, by distributing hydrostatic stresses and providing rigidity to the tire's casing ply.[1]

Global patent development

Global patent development in vehicle efficiency

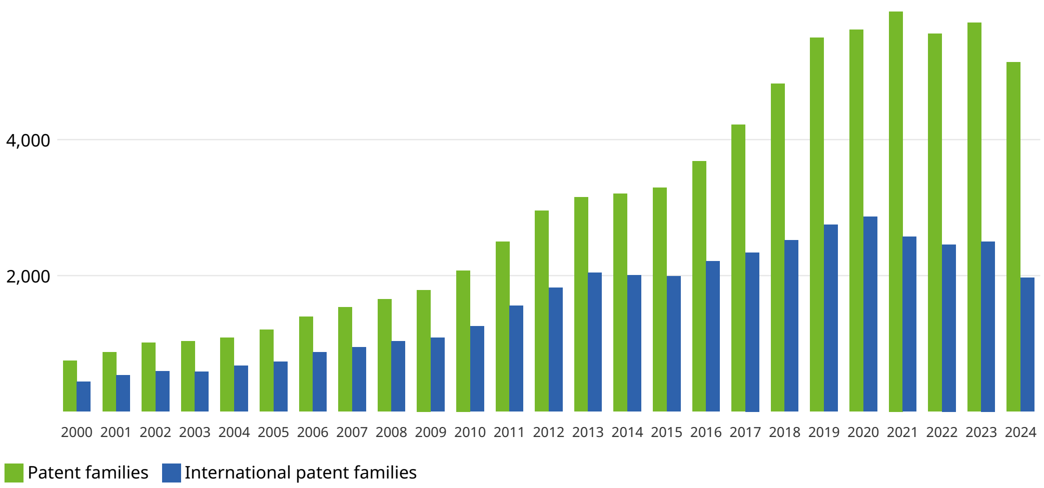
From 2000 to 2024, the volume of published patent families related to heavy-duty vehicle efficiency expanded substantially, growing from approximately 750 to more than 5,100 published families (Figure 5.1). International patent families (IPFs) followed a similar but slightly flatter trajectory, rising from 437 to just under 2,000. It is important to observe, however, that this growth trend peaked in 2021 with 5,884 publications (and in 2020 for IPFs); subsequent annual activity has decreased by roughly 13%.

A factor that probably played a role in the recent slowdown was the global semiconductor shortage and pervasive supply chain disruptions following the COVID-19 pandemic, which severely restricted production and led to significant revenue losses across the automotive industry. These factors compelled heavy-duty road transport companies to enact broad cost-reduction measures and prioritize patenting activities in other fields, such as low-emission energy sources and energy infrastructure.

1 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Patenting activity for vehicle efficiency technologies for heavy-duty road transport has risen dramatically since 2000, but has declined in recent years

Figure 5.1 Published patent families in vehicle efficiency for heavy-duty road transport by earliest publication year, 2000–2024



Note: International patent families represent inventions that are protected in multiple countries.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Comparison between vehicle efficiency technologies

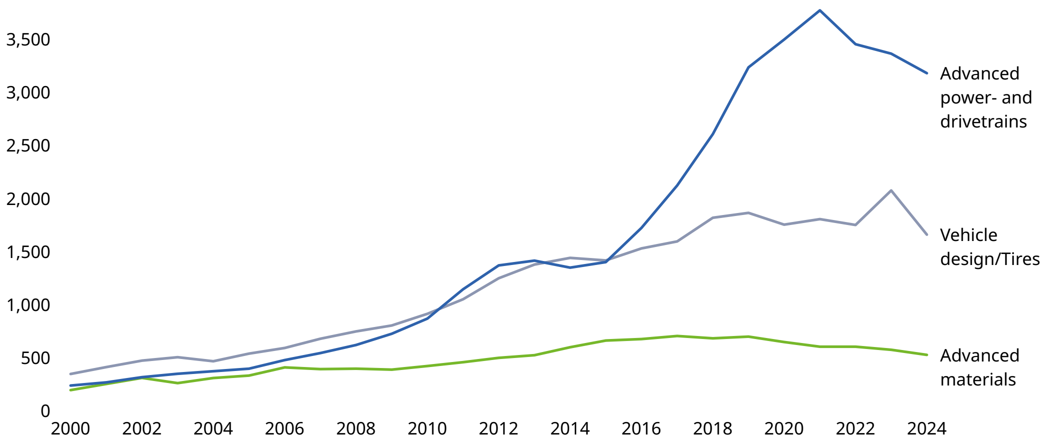
A closer analysis of patenting activity reveals that advanced power- and drivetrain technologies dominate the research landscape in the field of vehicle efficiency for heavy-duty road transport (Figure 5.2). The number of published patent families in this field has seen substantial growth, increasing from 234 in 2000 to 3,177 in 2024. This trend represents a compound annual growth rate (CAGR) of more than 11%.

Patenting activity in vehicle design and tire technologies also grew rapidly between 2000 and 2014 but has largely plateaued since then. One contributing factor to this stabilization is the technological maturity of core concepts, such as improved aerodynamics and low rolling-resistance tires. Although these areas continue to deliver incremental improvements, the remaining innovation potential tends to be smaller and results in fewer new patentable inventions.

Among the three technological subfields, advanced materials show the slowest long-term growth. Global published patent families only increased from 191 in 2000 to 523 in 2024, and current activity is approximately 25% below the peak levels reached in the mid-2010s. While materials research remains strategically important, its patenting intensity has not kept pace with power- and drivetrain innovations or vehicle design. As many high-performance materials – such as carbon-fiber composites – remain expensive to produce, their commercial uptake in cost-sensitive industries like heavy-duty logistics has remained modest. Because the efficiency gains from lightweighting often do not offset the high upfront costs, manufacturers have had weaker incentives to invest in new materials research, which may have contributed to slower innovation activity in this field.

Global research activities focus on advanced powertrain and drivetrain technologies

Figure 5.2 Published patent families in each type of vehicle efficiency for heavy-duty road transport by earliest publication year, 2000–2024



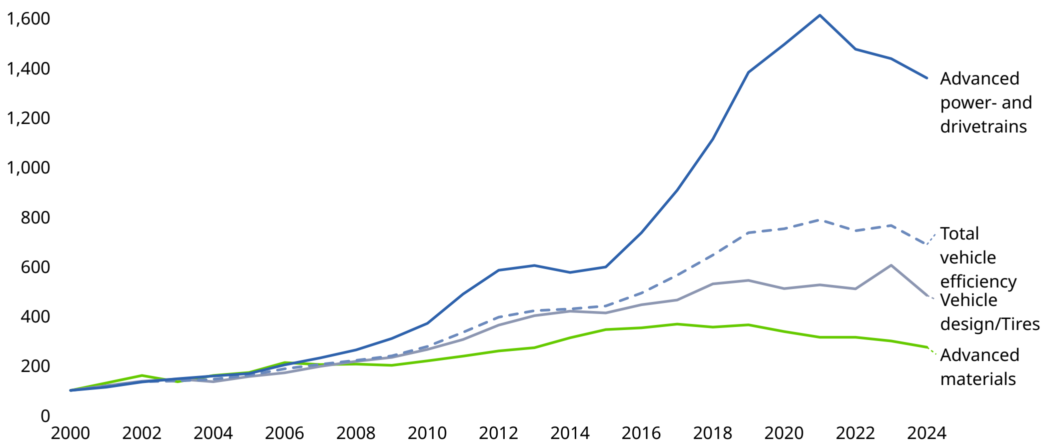
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patenting growth compared to other technologies

The development of published patent families in the field of heavy-duty vehicle efficiency demonstrates above-average innovation speed compared to both the overall patenting trends in heavy-duty road transport and total global patenting (Figure 5.3). While patenting activity across all areas of heavy-duty road transport shows only a moderate increase over the general technological average, the field of vehicle efficiency has experienced growth that is twice as high (+587% vs. +262% for the average of all technologies). This dynamic growth is attributable to the significant increase in patents related to advanced powertrains and drivetrains. However, other key areas of decarbonization in heavy-duty road transport (low-emission energy sources and energy infrastructure) have experienced even higher growth rates.

Patenting activity in vehicle efficiency for heavy-duty road vehicles has increased more dynamically than in other technological areas, but less so than in low-emission energy sources or energy infrastructure

Figure 5.3 Indexed development of global published patent families in vehicle efficiency, by publication year 2000–2024



Note: Indexed development is based on all patent families in the year 2000 being normalized to 100. Total vehicle efficiency refers to the sum of published patent families in advanced power- and drivetrain technologies, vehicle design and tires, as well as advanced materials for heavy-duty road vehicles.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

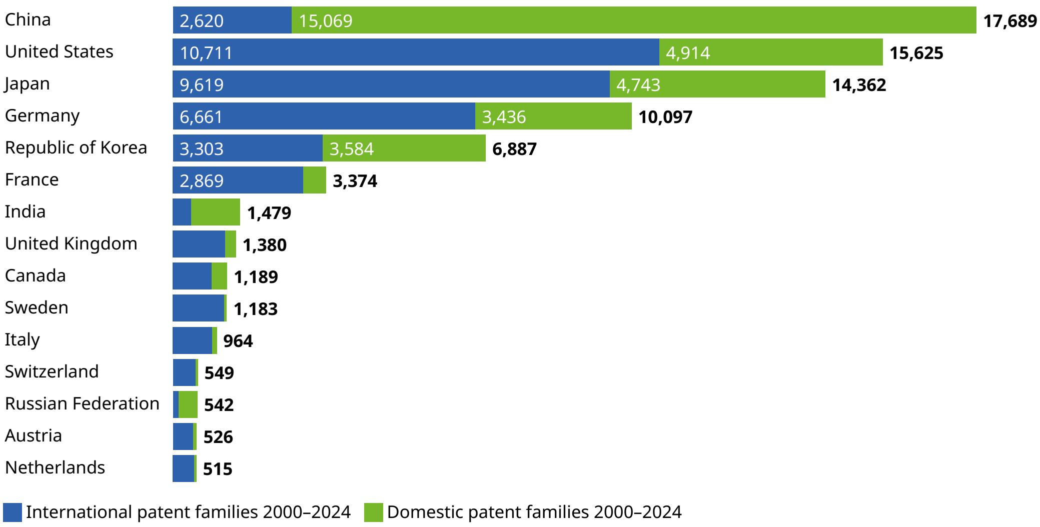
Top inventor locations

In the field of vehicle efficiency for heavy-duty road transport, China, the United States and Japan are in a close three-way competition for the top spot in patent publications the innovation lead (Figure 5.4). China tops the ranking with nearly 17,700 published patent families between 2000 and 2024, while the United States (15,625) and Japan (14,362) remain in close contention. Germany also plays a significant role, with over 10,000 published patent families during the same period, followed by the Republic of Korea with 6,887.

As observed in other areas of heavy-duty road transport decarbonization, the share of international patent families of all patent families originating from China (15%) is considerably lower than that of most other leading research countries.

China, the United States and Japan are leading the race in vehicle efficiency technologies for heavy-duty road transport

Figure 5.4 Total published patent families for the top inventor locations in vehicle efficiency technologies for heavy-duty road transport, 2000–2024



Notes: International patent families represent inventions that are protected in multiple countries.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent growth and specialization

Analysis of patenting activity over the past five years reveals significant geographical divergence (Figure 5.5). India has emerged as the fastest-growing innovation location in vehicle efficiency, showing a surge in patent publications from 66 in 2019 to 300 in 2024. This corresponds to a robust 35% CAGR. Sweden was the only other major research location to exhibit strong momentum, recording an average annual increase in published patent families of 11%.

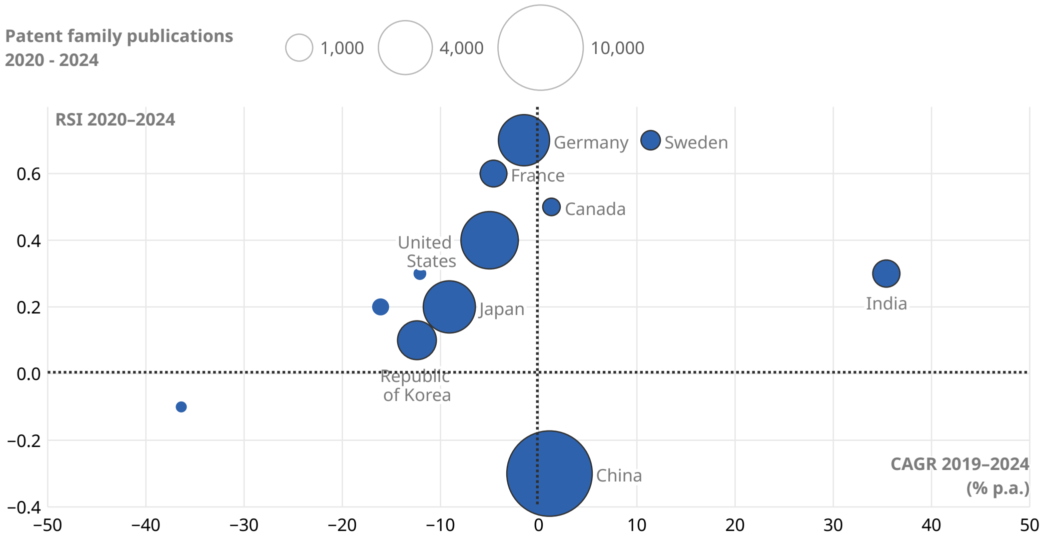
In contrast, patenting activity has largely stagnated over the past five years in Canada, China and Germany. In all the remaining major research countries, patenting activity has seen a decline, which is most pronounced in the Russian Federation.

When assessed by the relative specialization index (RSI), Sweden, Germany, Austria and France demonstrate the highest levels of relative specialization in heavy-duty vehicle efficiency technologies. Conversely, China's level of specialization remains the lowest among the top research locations.

These results mirror the patent trends observed in low-emission energy sources and energy infrastructure. This underscores the high degree of technological convergence in related heavy-duty transport areas.

India saw a rapid surge in patenting activity. Sweden, Germany, Austria and France remain the countries with the highest degree of specialization

Figure 5.5 Top inventor locations in vehicle efficiency for heavy-duty road transport, by number of published patent families (2020–2024), Relative Specialization Index (2020–2024) and compound annual growth rate, 2019–2024 (% p.a.)



Note: Circle size is proportional to the number of published patent families. The Relative Specialization Index (RSI) is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. The value of 1 indicates the maximum specialization, while the minimum value of –1 indicates zero specialization. An average global specialization level is indicated by a value of 0. The compound annual growth rate (CAGR) measures the average annual patent growth between 2019 and 2024 in percentages.

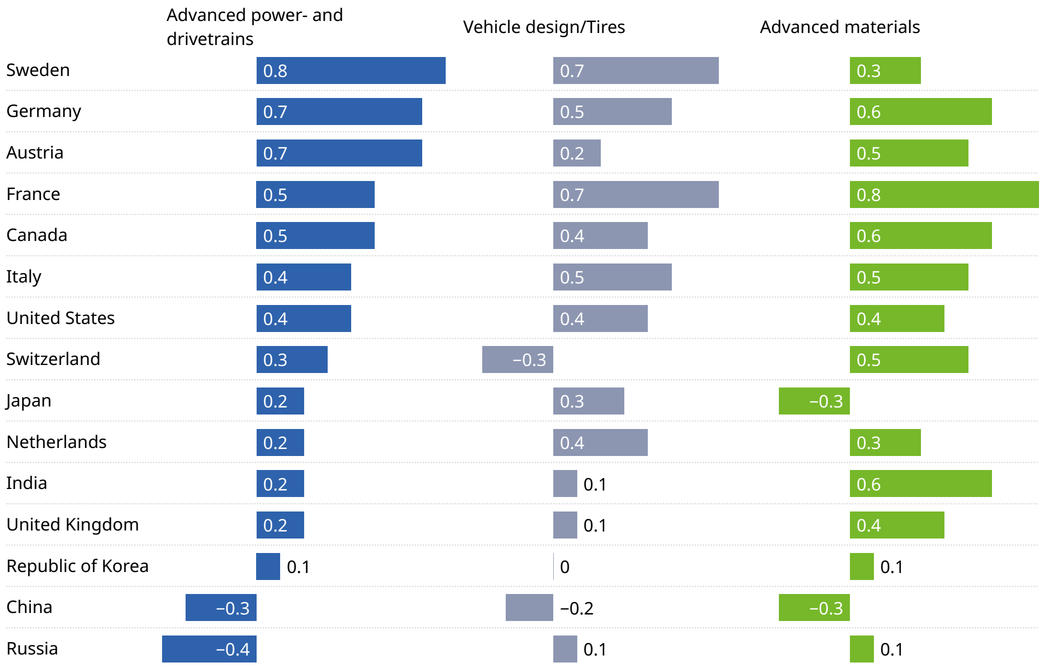
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Relative specialization in heavy-duty vehicle efficiency

Most top research countries show a high RSI in all three areas of vehicle efficiency for heavy-duty road transport (Figure 5.6). However, there are also some outliers that focus their research efforts mostly on a specific field. An example is Switzerland, which focuses on advanced materials and advanced power- and drivetrains, but is less specialized in vehicle design and tire technologies. Japan, in contrast, has a negative RSI in advanced materials but is highly specialized in vehicle design and tires, as well as advanced power- and drivetrains.

Most countries have a positive RSI value in all three vehicle efficiency technology areas

Figure 5.6 Relative Specialization Index (RSI) in different areas of vehicle efficiency for heavy-duty road transport for the top inventor locations, 2020–2024



Notes: The Relative Specialization Index (RSI) is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. The value of 1 indicates the maximum specialization, while the minimum value of –1 indicates zero specialization. An average global specialization level is indicated by a value of 0.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Research priorities

An analysis of research activities across the top locations shows that most countries concentrate their research on the development of advanced powertrains and drivetrains for battery-electric and fuel cell heavy-duty vehicles (Figure 5.7). Austria, Germany, Sweden, China and the Republic of Korea exhibit a particularly strong orientation toward this field, with patent families related to powertrain and drivetrain technologies accounting for more than 50% of all vehicle-efficiency patents in these countries.

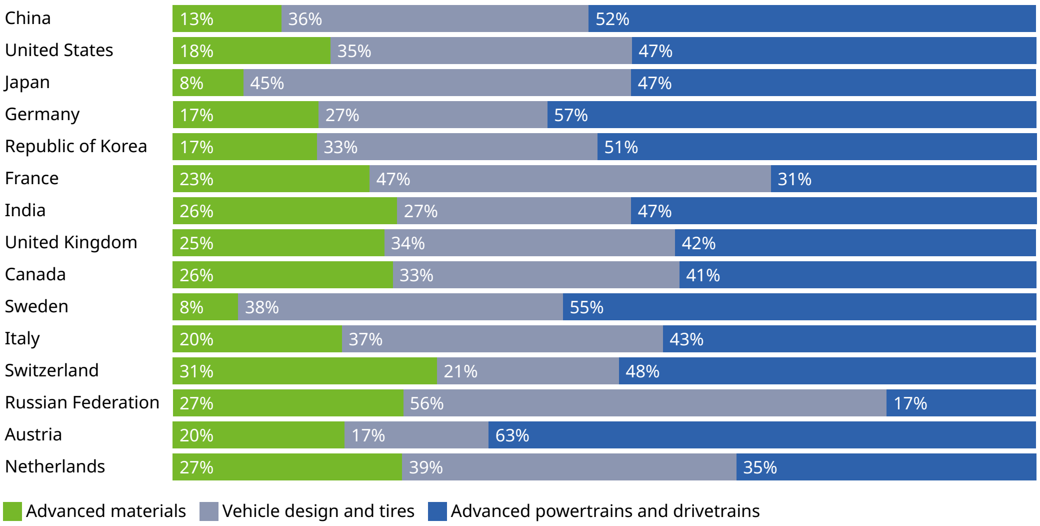
Vehicle design and tire technologies represent the second most prominent area of efficiency-related research across major innovation locations. This technology class covers aerodynamics, body and chassis optimization, lightweight structural components and, especially, low-rolling-resistance tire technologies. The share of patents in this field is particularly high in Russia (56%), France (47%) and Japan (45%). A key reason is the presence of several major global tire manufacturers in these countries – including Cordiant in the Russian Federation, Michelin in France and Bridgestone, Yokohama Rubber and Sumitomo Rubber Industries in Japan – whose long-standing research and development programs continue to drive innovation in tread design, rubber compounds and casing structures for heavy-duty vehicles.

Advanced materials play a smaller role globally but are especially prominent in Switzerland, where they account for 31% of vehicle-efficiency patents. This specialization benefits from Switzerland's strong materials science ecosystem, including universities and research institutes, such as ETH Zurich, that have research projects in the field of advanced lightweight materials for vehicles.[2]

2 Eberhard, A. (2020). Light, strong, and affordable. ETH Zurich. Available at: https://ethz.ch/en/news-and-events/eth-news/news/2020/11/faserverstaerkte-kunststoffe-herstellen.html.

Most locations focus on research on advanced powertrains and drivetrains

Figure 5.7 Research priorities in heavy-duty vehicle efficiency for the top inventor locations, by share based on published patent families, 2000–2024

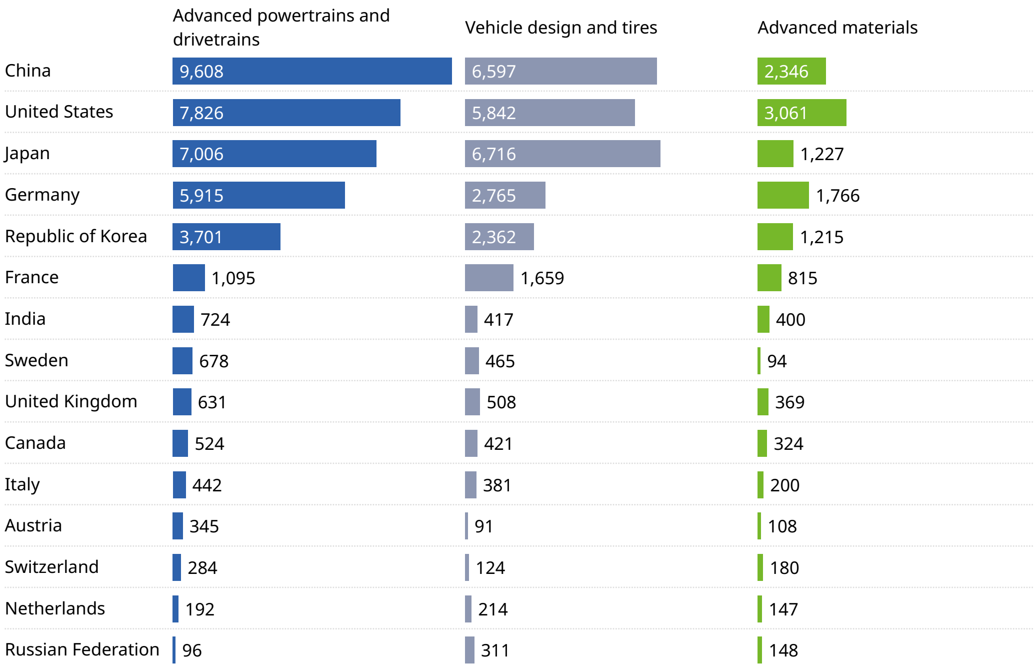


Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

The location ranking for the three areas of heavy-duty vehicle efficiency reflects the differences in research priorities (Figure 5.8). China leads in advanced powertrain and drivetrain innovation, with more than 9,600 patent families published since 2000 – highlighting its strong emphasis on electric vehicle development. The United States has published the greatest number of patent families in advanced materials (3,061), while Japan ranks first in vehicle design and tire technologies (6,716), just ahead of China (6,597).

The United States leads in advanced materials research, Japan in vehicle design and tires, and China in advanced powertrains and drivetrains

Figure 5.8 Research priorities for the top inventor locations in heavy-duty vehicle efficiency technologies, by number of published patent families, 2000–2024



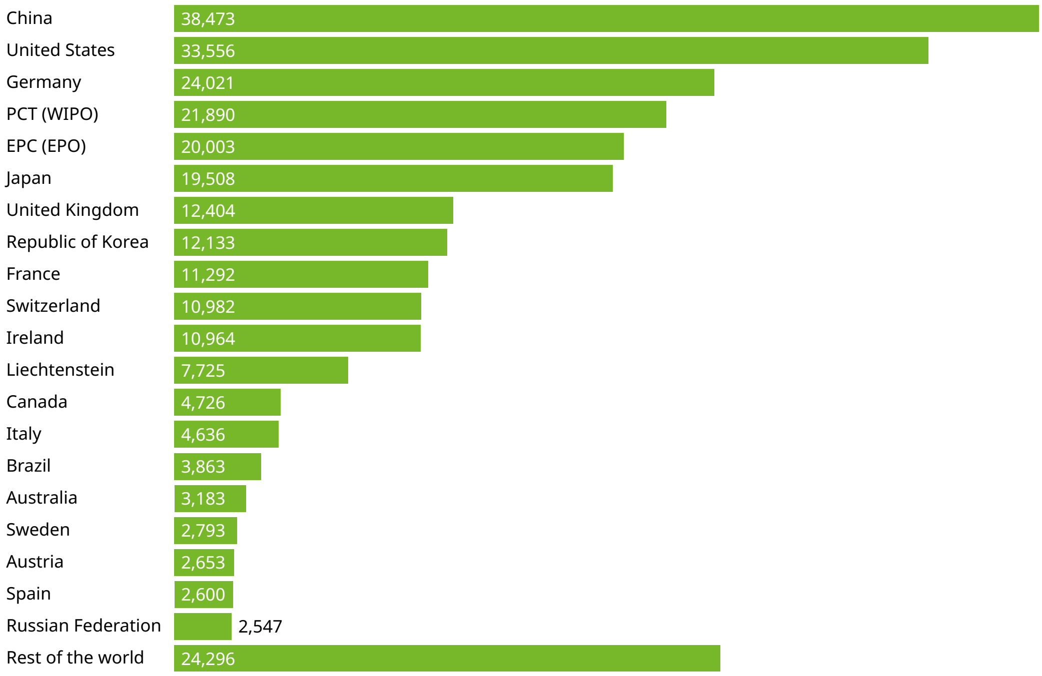
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Key filing jurisdictions

As shown in Figure 5.9, China and the United States are the leading jurisdictions for patent filings. Between 2000 and 2024, China recorded nearly 38,500 patents related to heavy-duty vehicle efficiency, while the United States recorded more than 33,500. Germany is another major filing location with 24,021 patents. Patent filings under the Patent Cooperation Treaty (PCT) and the European Patent Convention (EPC) represent the fourth- and fifth-largest filing routes, with nearly 21,900 and just over 20,000 applications submitted since 2000, respectively.

China and the United States are the top filing jurisdictions for heavy-duty vehicle efficiency technologies

Figure 5.9 Top patent-filing jurisdictions in heavy-duty road transport vehicle efficiency technologies, based on the number of published patent families, 2000–2024



Note: EPC is the European Patent Convention, EPO is the European Patent Office, PCT is the Patent Cooperation Treaty, WIPO is the World Intellectual Property Organization.

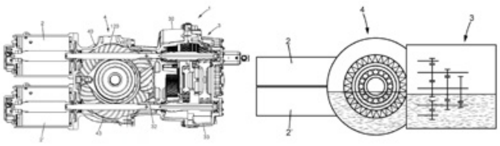
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent spotlight

A granted Volvo Truck patent covers an electric truck powertrain with a dry sump lubrication system that reduces splash losses, improves efficiency and enables a more compact, cost-effective design.

- Patent publication number: **US 11725722 B2**
- Owner: **Volvo Truck**
- Title: **Electric powertrain for truck**
- Publication date: **October 6, 2022**
- Grant date: **August 15, 2023**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=US376041106).

AI simulation

Source: AI-generated by WIPO.

Problem: Existing powertrain assemblies for electric and hybrid vehicles face high power losses and inefficiencies due to “splash losses” from wet sump lubrication systems, which require complex and costly oil-tight seals and separate lubrication systems for the gearbox and axle, limiting compactness and increasing costs.

Solution: A dry sump lubrication system is implemented, where a separate oil storage area is integrated within the axle oil sump, using a scavenge pump to retrieve oil from the gearbox sump and convey it to the storage area, and a main pump to distribute it to the gearbox gears, reducing oil levels and splash losses without the need for additional reservoirs or complex seals.

Benefit: This configuration significantly reduces splash losses and improves efficiency by eliminating the need for separate lubrication systems and oil reservoirs, enhancing the compactness and reducing the costs of the powertrain assembly while maintaining effective lubrication.[3]

Top patent owners

As in the case of low-emission energy sources and energy infrastructure, Toyota – Japan’s largest automotive manufacturer – holds the top position in the patent ranking for heavy-duty vehicle efficiency technologies, with 2,081 published patent families since 2000 (Figure 5.10). However, Toyota’s lead in this area is considerably narrower than in other segments. Sumitomo Rubber Industries (1,921), Volkswagen Group (1,796) and Hyundai Motor Company (1,732) follow close behind.

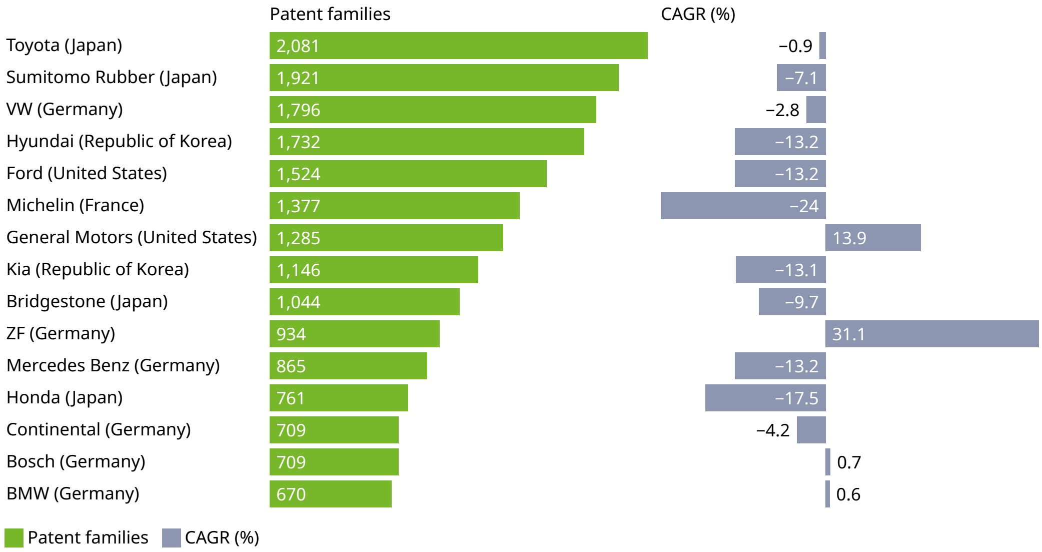
A key distinction from the findings in the low-emission energy sources and energy infrastructure chapters is the prominent role of tire manufacturers in the vehicle efficiency research landscape. Within the top 25 patent holders, roughly one-third are companies that are either fully dedicated to tire development or for whom tires represent a significant business segment. These include Sumitomo Rubber Industries, Michelin, Bridgestone, Continental, Goodyear, Yokohama Rubber and Toyo Tire.

The remainder of the top 25 is composed primarily of major vehicle manufacturers, including Ford, General Motors (GM) and Kia, as well as major automotive suppliers, such as ZF and Bosch. The highest-ranked non-automotive companies appear only at the 19th and 25th positions – CRRC and Siemens, respectively.

3 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Toyota is ahead in the patent race in heavy-duty vehicle efficiency, but Sumitomo Rubber, VW and Hyundai are close behind

Figure 5.10 Top patent owners in heavy-duty vehicle efficiency technologies, by number of published patent families, 2000–2024 and their annual patent publication growth rate, 2019–2024



Note: CAGR is compound annual growth rate.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent growth

Recent patent trends indicate that Volvo and ZF have achieved the strongest growth in their patent portfolios related to heavy-duty vehicle efficiency over the past five years. Volvo, for example, is developing next-generation e-axles for its electric trucks. By integrating key driveline components directly into the axle housing, Volvo's e-axle architecture reduces system weight and frees up space for additional battery capacity, thereby extending range without compromising payload. ZF has likewise expanded its innovation efforts. In 2024, the company introduced a new electric central drive for heavy-duty trucks that enables original equipment manufacturers (OEMs), such as Ford, to electrify existing truck platforms with minimal redesign. Because the unit fits into the same installation space as a conventional internal combustion engine transmission, manufacturers can electrify vehicles while maintaining assembly processes and chassis layouts largely unchanged, thereby accelerating the transition to electric heavy-duty drivetrains.[4]

Goodyear, General Motors, BYD and Toyo Tire have also increased their patenting activity dynamically since 2019, while the patenting activity of some companies, such as Yokohama Rubber, Honda and Michelin, has declined noticeably.

Research priorities

Most of the top research companies show a clear concentration of their research and development efforts in the development of advanced powertrains and drivetrains for heavy-duty vehicles (Figure 5.11). Major automotive OEMs – including Toyota, VW, Hyundai and Ford – are strong examples, with the majority of their efficiency-related patents originating from innovations in electric motors, e-axles, hybrid systems, transmission architectures and power electronics.

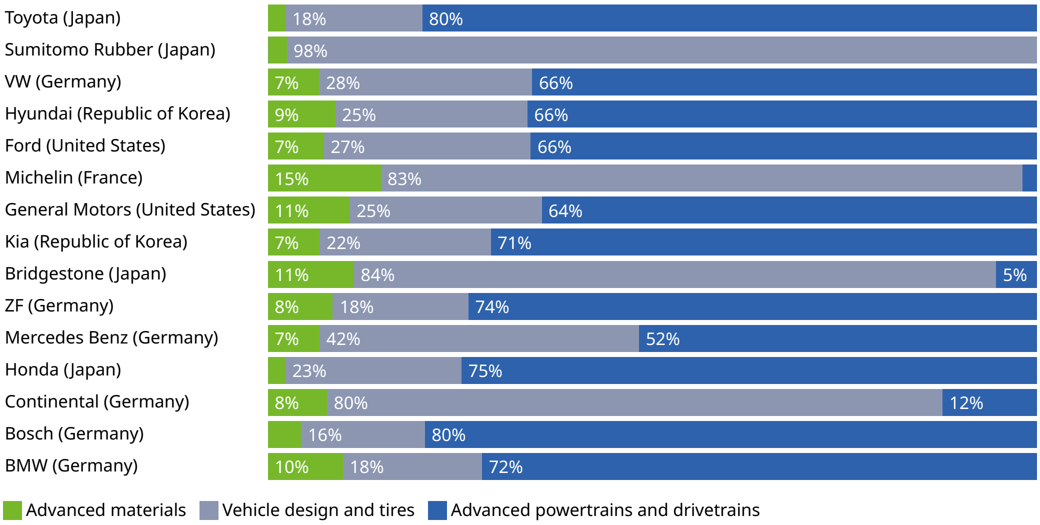
4 Girling, W. (2024). Flexibility informs electric truck drivetrain innovation. Automotiveworld. Available at: https://www.automotiveworld.com/articles/flexibility-informs-electric-truck-drivetrain-innovation.

By contrast, leading tire manufacturers, such as Sumitomo Rubber, Michelin, Bridgestone, Continental, Goodyear, Yokohama Rubber and Toyo Tire – unsurprisingly – focus almost exclusively on vehicle design and tire technologies. Their patent portfolios revolve around tread compounds, rolling-resistance reduction, durability improvements and aerodynamically optimized tire and wheel designs.

Advanced materials account for a relatively small share of patenting activity for most companies in the data set. However, they represent a substantial portion of the research activity for a few specialized firms. Notably, Chinese CRRC stands out, with advanced materials representing 42% of its vehicle-efficiency patent portfolio, driven by its expertise in lightweight composites and high-performance materials. While CRRC's research activities are railway-oriented, the underlying materials know-how (composites, lightweight load-bearing structures) is transferable to heavy-duty road vehicles. Siemens, likewise, shows a comparatively high share (24%), reflecting its work on high-efficiency motor components and thermal management materials.

Advanced powertrains and drivetrains are the most important research area for the majority of the top patent owners

Figure 5.11 Research priorities of the top patent owners in heavy-duty vehicle efficiency technologies, based on the number of published patent families, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Top patent owners in heavy-duty vehicle efficiency technologies

Toyota is the leading patent holder in advanced powertrains and drivetrains, reflecting its long-standing focus on next-generation propulsion technologies. The remainder of the top patent owners in this category consists primarily of major car and truck manufacturers and automotive suppliers. One notable exception is Kubota, an agricultural machinery producer, which appears in 15th place.

In the area of advanced materials, the ranking is more diverse. Michelin holds the top position, driven by its intensive research and development program in high-performance elastomers, composites and sustainable tire materials. CRRC follows close behind, highlighting the spillover of materials innovation from the rail sector into heavy-duty road transport. Hyundai ranks third, supported by its broad materials research for lightweight vehicle structures and next-generation batteries.

In vehicle design and tires, specialist tire manufacturers dominate the landscape. Sumitomo Rubber, Michelin and Bridgestone occupy the top positions, reflecting their strong innovation focus on tire construction and rolling-resistance reduction. However, the field also includes several major truck manufacturers – including VW, Hyundai and Ford – which hold substantial portfolios of design-related patents due to their work on chassis optimization and aerodynamic truck design.

6 Digitalization: fleet and operations management

Digitalization technologies are becoming an important complement to the decarbonization of heavy-duty road transport by optimizing vehicle operations, logistics and energy use. Patent analysis of "green digitalization" inventions highlights rapid growth in areas such as autonomous driving, connected vehicles and fleet optimization.

The convergence with digital technologies

Decarbonizing heavy-duty road transport depends primarily on making a transition to low-emission energy sources and the rollout of suitable energy infrastructure. But digitalization – comparable to vehicle efficiency technologies – has an important complementary role to play. Much like aerodynamic enhancements or lightweighting, digital tools do not in themselves replace the need for clean energy, but rather optimize its use. The convergence of automotive engineering with digital technologies is driving a new wave of patenting activity focused on the following key areas:

- Autonomous driving technologies can reduce emissions by optimizing driving behavior, improving safety and smoothing traffic flows. Advanced driver-assistance systems (ADAS), automated braking, lane-keeping and sensor fusion systems lower fuel use and minimize congestion or accident-related energy losses. Future autonomous trucks could further enhance efficiency through the imposition of consistent driving patterns and coordinated platooning, whereby multiple trucks travel closely together at automated, synchronized speeds to reduce aerodynamic drag and lower overall energy consumption.
- Navigation and GPS systems have evolved into sophisticated optimization tools. Today they integrate real-time traffic data, road grade information, weather conditions, and charging or refueling availability. For heavy-duty vehicles, this enables energy-efficient routing, minimizes downtime and supports range management for battery-electric and fuel cell trucks.
- Further important aspects of transport digitalization are connected vehicles and road-traffic interaction – the real-time coordination between vehicles, infrastructure and traffic management systems. Road-traffic interaction technologies use connectivity, sensors and AI-based prediction models to optimize how vehicles move through the road network. This connectivity supports collision avoidance, dynamic route optimization, predictive maintenance, and real-time energy management. For heavy-duty road transport, it helps ensure that zero-emission trucks operate at optimal efficiency and charging or refueling is synchronized with operational needs. The relevance of these technologies is illustrated in a recent joint study by autonomous logistics company Einride and Fraunhofer ISI showing that AI-based planning optimization for freight operations significantly increases the operational efficiency of electric trucks and reduces the overall cost of ownership.[1]
- Smart city technologies enhance the overall efficiency of urban mobility by synchronizing transport flows, traffic signals and freight movement. For heavy-duty vehicles such as buses, smart traffic management can reduce stop-and-go driving, as well as mitigate congestion in dense urban environments.
- Urban logistics and automated warehousing are transforming the distribution chain. Automated warehousing systems, digital inventory management and optimized loading/unloading processes reduce dwell time and improve fleet utilization. Urban consolidation centers and digitally coordinated last-mile logistics help decrease the number of vehicle kilometers traveled.

It is important to note that the primary driver for most digitalization technologies, such as route optimization or automated logistics, is to increase revenues and profit margins through operational speed and cost reduction. However, these innovations can also play a part in decarbonization. By optimizing routing, reducing idle times, enabling predictive maintenance, coordinating freight flows and improving system-wide logistics, digital tools help lower energy consumption, maximize the utilization of low-emission vehicles and support more efficient transport operations.

In the patent analysis conducted for this chapter, AI-based patent evaluation has been used to identify only those patents in digitalization technologies that contain inventions relevant to reducing CO_2 emissions in heavy-duty road transport – referred to throughout the chapter as green digitalization (see Appendix for more details).

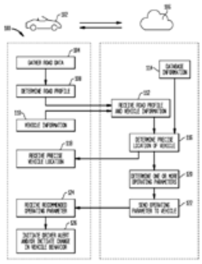
1 Engholm *et al.* (2025). Beyond replacing diesel trucks: How optimized fleet planning increases electrification and lowers transportation costs. Fraunhofer Institute for Systems and Innovation Research ISI. Available at: https://publica.fraunhofer.de/entities/publication/dc780649-f9c4-4d1f-99bc-617dd591ea06.

Patent spotlight

A Clearmotion patent application – which is suitable for heavy-duty road transport – describes a terrain-based vehicle localization system that improves control, anticipates road surface featuresand enhances comfort, durabilityand computational efficiency.

– Patent publication number: **WO 2022/146866 A1**
– Owner: **Clearmotion**
– Title: **Systems and methods for vehicle control using terrain-based localization**
– Publication date: **July 7, 2022**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2022146866)

AI simulation

Source: AI-generated by WIPO.

Problem: Current vehicle localization systems, particularly those relying on global navigation satellite systems (GNSS), lack sufficient accuracy and resolution for advanced driver assistance systems and autonomous driving features, leading to inadequate control of vehicle systems when interacting with road surface features like potholes and bumps.

Solution: Implementing a terrain-based localization method that uses road surface data from sensors to determine vehicle position, comparing measured road profiles with reference profiles, and employing dead reckoning and GNSS tracking to reduce computational and network bandwidth requirements, allowing for discretized and intermittent data comparisons to enhance localization accuracy.

Benefit: This approach provides more accurate and efficient vehicle control by enabling better anticipation and response to road surface features, improving occupant comfort and vehicle durability while reducing computational and network demands.[2]

Global patent development

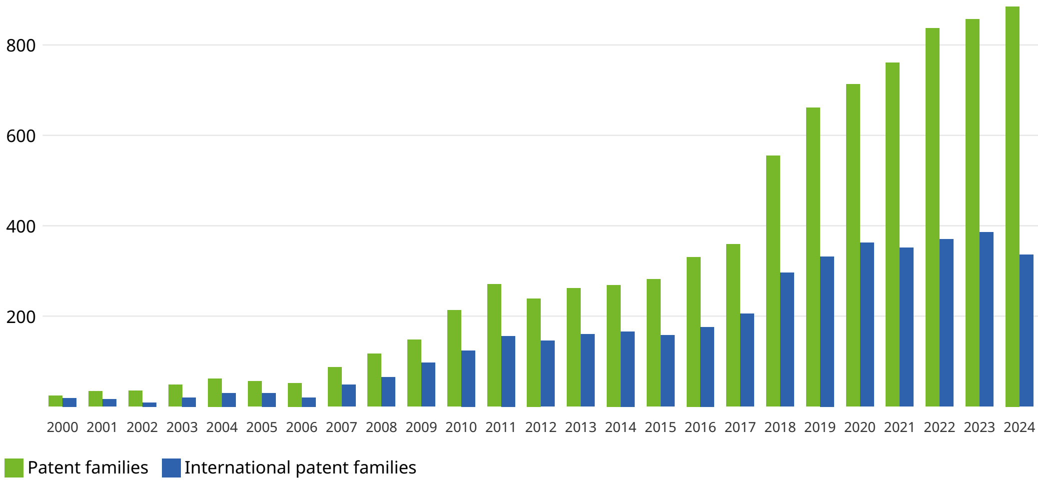
Global patent development in green digitalization of heavy-duty road transport

Between 2000 and 2024, the number of published patent families in green digitalization technologies for heavy-duty road vehicles rose steadily from 24 to over 885 (Figure 6.1). International patent families (IPFs) showed slower growth, rising from 19 to 336. Although patenting activity in green digitalization remains considerably smaller than in the other key technology areas (low-emission energy sources, energy infrastructure and vehicle efficiency), it has seen the highest growth rate, with no dip in activity in 2024, unlike in the other areas. This demonstrates that research in green digitalization continues to gain relevance for heavy-duty road transport.

2 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

Patenting activity in green digitalization technologies has risen steadily, but volume remains smaller than for other key heavy-duty technology areas

Figure 6.1 Published patent families in green digitalization for heavy-duty road transport by earliest publication year, 2000–2024



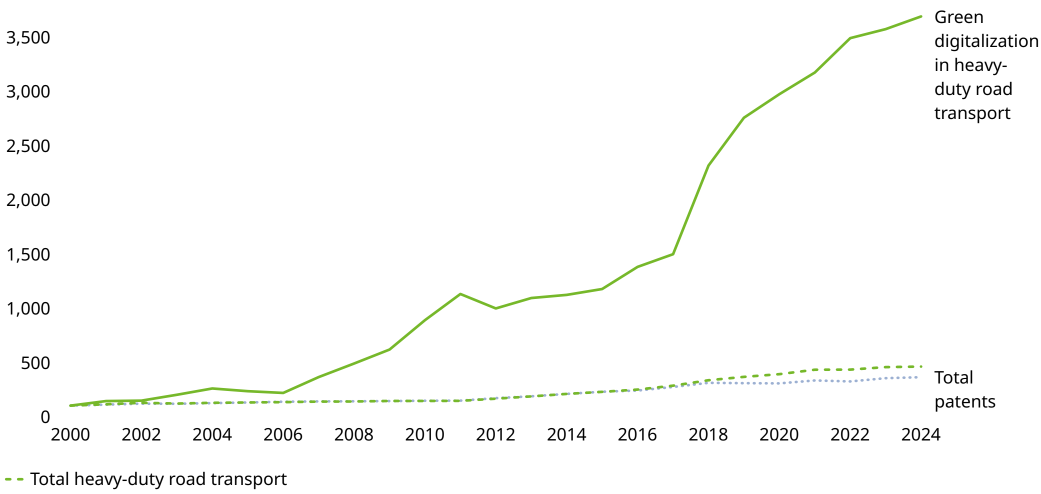
Note: International patent families represent inventions that are protected in multiple countries.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patenting growth compared to other technologies

Patenting in green digitalization technologies for heavy-duty road transport has experienced the strongest growth of all technology areas analyzed in this report – far outpacing overall global patenting trends (Figure 6.2). Since 2000, annual patenting activity in this field has increased over 3,600%, although this surge began from a relatively low baseline.

Patenting activity in green digitalization for heavy-duty road vehicles has grown faster than patenting in the total sector

Figure 6.2 Indexed development of global published patent families in green digitalization for heavy-duty road transport compared to the development of all heavy-duty road transport patent families and total patents, 2000–2024



Note: Indexed development is based on all patent families in the year 2000 being normalized to 100. Total heavy-duty road transport refers to all patenting activity in the heavy-duty road transport sector, including green digitalization, as well as other technologies (e.g., engines). Total patents refers to the overall number of published patent families across all technology fields worldwide, and is not limited to transport.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

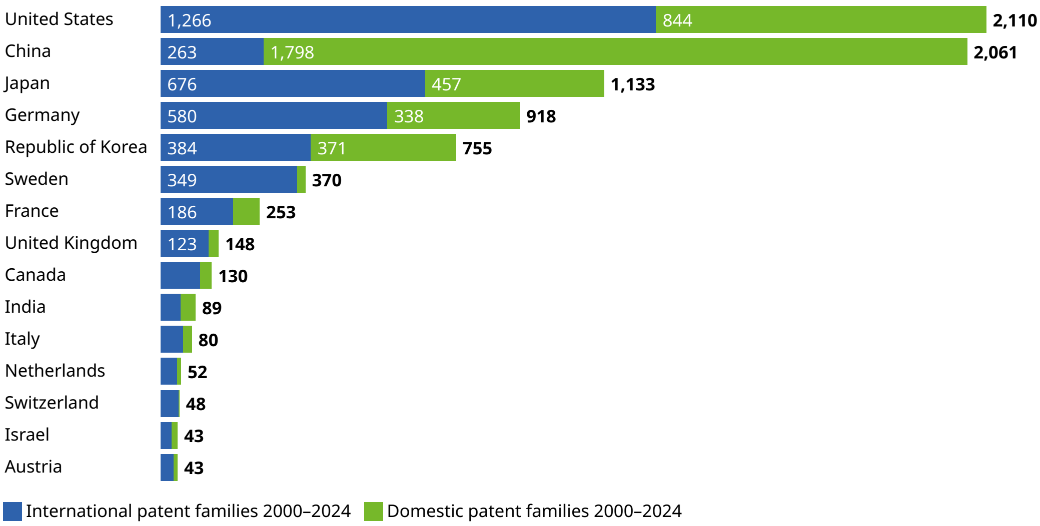
Top inventor locations

The United States and China lead in innovation for green digitalization in the field of heavy-duty road transport, as illustrated by their strong performance in terms of published patent families (Figure 6.3). Between 2000 and 2024, both these two locations were responsible for around 2,100 published patent families. Japan (1,133), Germany (918), and the Republic of Korea (755) complete the top five key research locations worldwide.

As outlined in previous chapters, China places a significantly stronger emphasis on domestic-only patents compared to the United States and the majority of other major research locations.

The United States and China have published the most patent families in green digitalization technologies for heavy-duty road transport

Figure 6.3 Total published patent families for the top inventor locations in green digitalization technologies for heavy-duty road transport, 2000–2024



Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

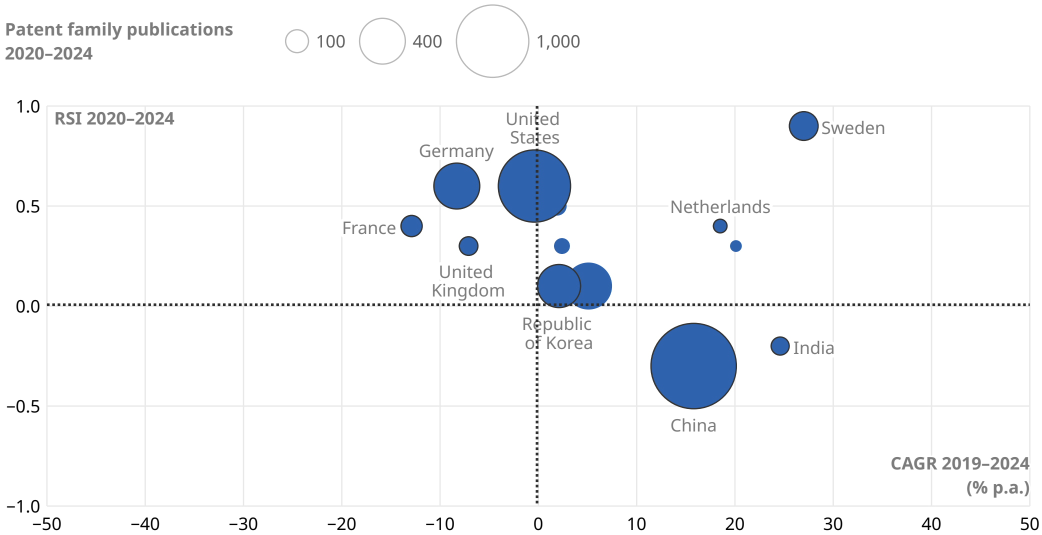
Patent growth and specialization

Sweden has achieved the highest patent growth rate in the area of green heavy-duty road transport digitalization over the past five years, at a compound rate of 27% per annum (Figure 6.4). India, Israel, the Netherlands and China have also demonstrated notable double-digit growth. In contrast, patenting activity has stagnated in the United States since 2019 and declined in Germany, the United Kingdom, France and Austria.

In terms of relative specialization (RSI), Sweden once again achieves the highest ranking, followed by Germany, the United States and Canada. In contrast, both China and India have below-average levels of specialization.

Sweden is the growth leader and most specialized location in green digitalization technologies for heavy-duty road transport

Figure 6.4 Top inventor locations in green digitalization for heavy-duty road transport, by number of published patent families (2020–2024), Relative Specialization Index (2020–2024) and compound annual growth rate, 2019–2024 (% p.a.)



Note: Circle size is proportional to number of published patent families. The Relative Specialization Index (RSI) is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. A value of 1 indicates the maximum specialization, while the minimum value of –1 indicates zero specialization. An average global specialization level is indicated by a value of 0. The compound annual growth rate (CAGR) measures the average annual patent growth between 2019 and 2024 in percent.

Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Top patent owners

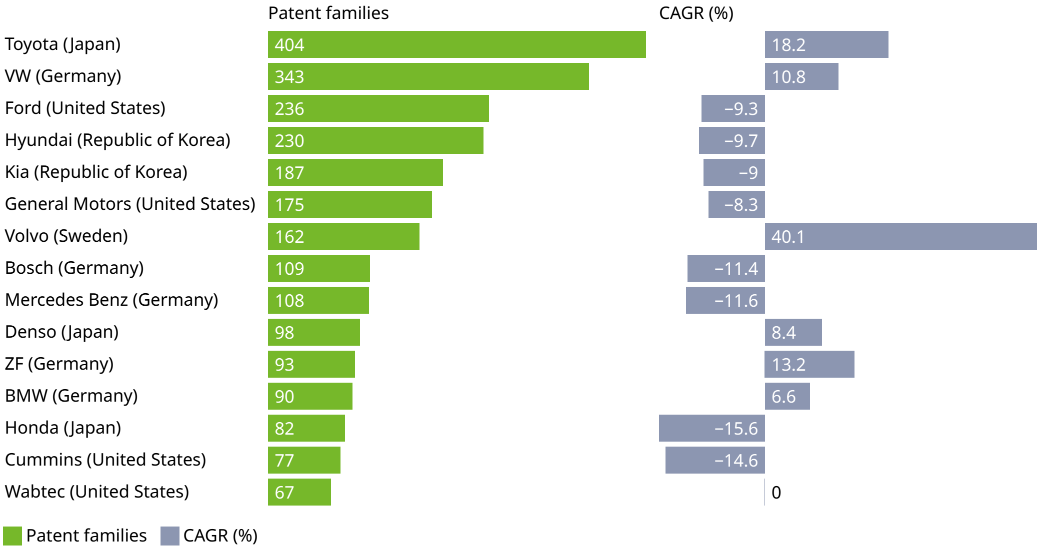
The list of leading research entities in green digitalization technologies for heavy-duty vehicles closely mirrors the patterns observed for low-emission energy sources (Chapter 3), energy infrastructure (Chapter 4) and vehicle efficiency (Chapter 5). As is the case in these other areas, Toyota remains the largest patent owner, and the top 25 ranking is again dominated by major global automakers and suppliers, including VW (via Traton), Ford, Hyundai, Kia, General Motors, Volvo, and Bosch (Figure 6.5).

However, some companies that appear in the top 25 for green digitalization do not feature in any other technology rankings. They include two firms whose core business lies in electronics and software rather than vehicle manufacturing – Republic of Korea technology conglomerate LG Electronics and US semiconductor company Qualcomm. These two companies have recently cooperated in the introduction of a cross-domain controller platform capable of managing multiple vehicle functions simultaneously, including navigation, safety systems and ADAS.[3] Their presence among the top research companies highlights the increasing importance of digital and connectivity-driven innovation in heavy-duty road transport.

3 LG Electronics (2025). LG introduces integrated controller platform for vehicles at CES 2025. Available at: https://www.lgcorp.com/media/release/28532.

Toyota and VW lead the patent race in green digitalization for heavy-duty vehicles

Figure 6.5 Top patent owners in green digitalization for heavy-duty road transport, by number of published patent families, 2000–2024, and annual patent publication growth rate, 2019–2024



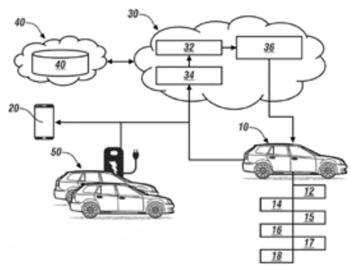
Note: CAGR is compound annual growth rate.
Source: WIPO, based on patent data from EconSight/IFI Claims, October 2025.

Patent spotlight

This General Motors granted patent – which is suitable for heavy-duty road transport – describes a system that ranks electric vehicle (EV) charging stations by route, cost, waiting time and user preferences, improving charging efficiency and reliability, supporting decarbonization and increasing operational efficiency and daily mileage for heavy-duty electric trucks.

- Patent publication number: **US 11203268 B2**
- Owner: **General Motors**
- Title: **Electric powertrain for truck**
- Publication date: **July 15, 2021**
- Grant date: **December 21, 2021**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=US330897393)

AI simulation

Source: AI-generated by WIPO.

Problem: Electric vehicle owners face challenges in selecting the most convenient and cost-effective charging stations based on their travel routes and preferences, as existing systems do not efficiently integrate factors like charging cost, waiting time, route deviation, and user preferences into the selection process.

Solution: A method and system that determines the state of charge of an EV's direct current (DC) power source and ranks nearby charging stations based on user-selectable parameters such as charging cost, waiting time, route deviation, and customer reviews, using a weighting factor algorithm to prioritize stations according to user preferences, facilitating the selection and scheduling of the best charging station.

Benefit: This solution reduces waiting time and travel distance by optimizing the selection of charging stations according to user preferences, ensuring a more efficient and convenient charging experience for EV owners.[4]

Patent growth

Recent patent trends show two companies – Geely and Volvo – stand out in terms of patent dynamics in green digitalization technologies for heavy-duty road transport, with Geely having increased compound annual patenting activity by around 45% and Volvo by around 40%. One example of Geely's activities is its strategic partnership with autonomous-vehicle technology provider Foretellix, aimed at integrating advanced simulation, verification and validation tools into its autonomous driving development processes.[5] Meanwhile, Volvo has taken major steps in digital transformation by launching Coretura, a joint venture with Daimler Truck to develop a software-defined vehicle platform and operating system that will enable more connected, adaptable and efficient heavy-duty commercial vehicles, reflecting a strategic push toward software-centric transport solutions.[6]

Jens Hügel, Senior Adviser, International Road Transport Union (IRU)

The next greatest technological revolution for heavy-duty road transport

Software defined vehicles (SDV) technology will most likely be the next greatest technological revolution for trucks and buses. Zero-emission powertrains and ADAS are pushing current vehicle data exchange networks (CAN) to the limit due to the amount of data and the need for faster and more accurate diagnostics to ease a transition toward new engine types. It is believed that, once vehicles are electrified with a backbone made of more resilient electronics, autonomous driving would meet its enabling conditions for deployment. Progress on SDVs varies greatly worldwide. While US and EU stakeholders are just getting started, Chinese OEMs are already putting SDV-equipped vehicles on the road, although in limited numbers, the technology being used to extend operational range for the same battery pack.

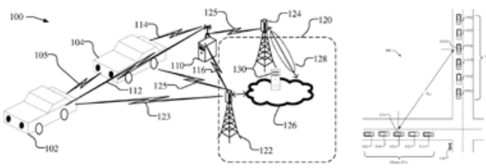
4 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.
5 Foretellix (2024). Foretellix and Geely partner to accelerate AV development. Available at : https://www.foretellix.com/foretellix-and-geely-partner-to-accelerate-av-development.
6 Volvo (2025b). Volvo Group and Daimler Truck launch Coretura – A joint venture to unlock the digital future of commercial vehicles. Available at: https://www.volvogroup.com/en/news-and-media/news/2025/jun/volvo-group-and-daimler-truck-launch-coretura---a-joint-venture-to-unlock-the-digital-future-of-commercial-vehicles.html.

Patent spotlight

A Qualcomm patent applicatdescribing a cluster-based vehicle positioning method for platooning and autonomous trucking that reduces communication overhead, while maintaining accurate inter-vehicle distance estimation.

- Patent publication number: **IN 202227046518 A**
- Owner: **Qualcomm**
- Title: **A cluster-based approach to positioning of vehicles in vehicle platooning or autonomous trucking**
- Publication date: **October 21, 2022**

Patent drawing



Source: PATENTSCOPE (https://patentscope.wipo.int/search/en/detail.jsf?docId=IN377284700)

AI simulation

Source: AI-generated by WIPO.

Problem: Current positioning techniques in wireless communication systems for vehicle platooning require all vehicles to broadcast ranging signals, leading to inefficiencies and increased overhead, especially when determining inter-cluster distances is more critical than intra-cluster distances.

Solution: A method where a designated representative vehicle in each cluster broadcasts ranging signals on behalf of the cluster to determine inter-cluster distances, minimizing overhead until intra-cluster distances become relevant, at which point all vehicles within the cluster begin broadcasting.

Benefit: This approach reduces the overhead of ranging signal broadcasts, conserves power, and improves positioning accuracy when necessary, while maintaining efficient communication and safety between clusters.[7]

7 Problem, solution and benefit summaries are AI-generated by Patsnap and do not represent WIPO interpretations.

7 IRENA analysis: pathways, policies and enablers for zero-emission trucks and buses

This chapter, prepared by the International Renewable Energy Agency (IRENA), emphasizes electrification as the dominant solution for decarbonizing heavy-duty road transport, supported by rapid battery cost declines, improving vehicle range, and emerging charging infrastructure. While biofuels and hydrogen play complementary roles, policy, infrastructure, and business model innovation are critical enablers to accelerate the transition toward zero-emission freight and passenger transport.

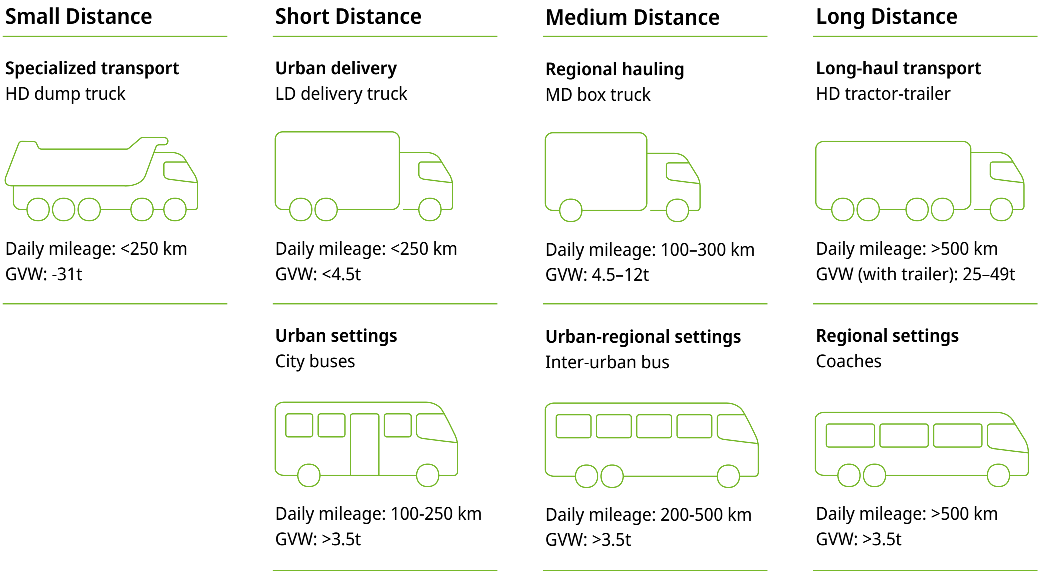
Status quo of heavy-duty road transport

Road freight is responsible for approximately 40% of road transport's total energy consumption. It is expected that energy use for heavy-duty trucks will rise to 25% by 2035, accounting for 80% of the growth in energy demand in the road freight sector.[1] According to IRENA's 1.5°C Scenario in the World Energy Transition Outlook, the share of renewable electricity in the transport sector needs to reach 84% by 2050.[2]

Heavy-duty trucks and buses are key modes of transport that play a vital role in the global economy, especially for freight and passenger transport. A schematic overview of the different categories for heavy-duty trucks can be found in Figure 7.1. As can be seen, heavy-duty trucks come in different configurations and cater to different sectors, depending on design and efficiency profile. More than 80% of rigid heavy-duty vehicles have a daily mileage of less than 500 km, and approximately 80% of tractor trailers travel less than 600 km of daily – a distance that can already be covered by a single charge in new vehicles.[3]

The different types of low emission truck options

Figure 7.1 Overview: heavy-duty trucks profiles and usage



Note: GVW is the gross vehicle weight, LD is light-duty, MD is medium-duty, HD is heavy-duty.
Source: WIPO, redesigned from Zhang *et al.*, 2025.

There are different categories of bus. City buses are passenger vehicles that have a gross vehicle weight (GVW) above 3.5 tonnes (t) and are used only in urban contexts. Inter-urban buses have a similar profile to city buses, but are also used in regional settings. Coaches are buses that are used primarily for regional transport.[4]

Heavy-duty trucks and buses together account for 8–9% of global vehicle stock,[5] yet they are responsible for almost a quarter of all transport-related CO_2 emissions. In 2024, global CO_2

1 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
2 IRENA (2024d). *World Energy Transitions Outlook 2024: 1.5°C Pathway*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024.
3 Speth and Plötz (2024) "Depot slow charging is sufficient for most electric trucks in Germany", Transportation Research Part D: Transport and Environment, vol. 128, https://doi.org/10.1016/j.trd.2024.104078
4 ICCT (2024). Race to Zero European heavy-duty vehicle market development quarterly (January–December 2023)", https://theicct.org/publication/race-to-zero-eu-hdv-market-development-q4-2023-mar24/
5 IEA (2024a). *Global EV Outlook 2024*. Paris: International Energy Agency. Available at: www.iea.org/reports/global-ev-outlook-2024, (2025e). *World Energy Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/world-energy-outlook-2025; IRENA (n.d.). Decarbonising hard-to-abate sectors with renewables: Enablers and recommendations. International Renewable Energy Agency. Available at: https://www.irena.org/Decarbonising-hard-to-abate-sectors-with-renewables-Enablers-and-recommendations.

emissions from heavy-duty trucks were approximately 1.96 gigatonnes (Gt).[6] Buses alone were responsible for emitting more than 0.5 Gt of CO_2 in 2022.[7] Emissions like PM, NO_x, etc. from heavy-duty trucks and buses are greater than those from the international aviation and shipping sectors combined – reflecting the outsized environmental impacts of these two segments. This higher emissions share is primarily attributable to the current dependence on fossil fuels as an energy source. Moreover, this is compounded by the fact that truck and bus transport are flexible, modular and wide ranging, given that combined they carry a significant amount of freight and people. Most of the heavy-duty trucks and buses on the roads today are powered by diesel (95% of consumption). Some of these vehicles run on petrol or natural gas, while a very small number of trucks are powered by biofuels being blended with fossil fuels (accounting for less than 5% of total consumption).[8]

Despite the current predominance of fossil fuels, the decarbonization of the road transport sector is approaching a turning point. Driven by technological progress and growing regulatory and market pressures, it is set to accelerate in the coming years. The growth in zero-emission vehicles is due to the increasing penetration of clean energy sources in energy systems, along with technological cost competitiveness and efficiency. The other driver for the adoption of sustainable trucks and buses is their competitive total cost of ownership compared to fossil fuel variants.[9] The Zero-Emission Technology Inventory database shows that 161 heavy-duty truck models currently exist or have been announced of which 135 are battery-electric and the other 26 fuel cell-based. The availability of vehicles with a maximum potential range of 805 kilometers (km) indicates promising capabilities for longer hauls. [10]

While zero-emissions heavy-duty vehicles are progressively increasing in market share, there have also been efficiency improvements to those heavy-duty vehicles currently on the road. For instance, the emission intensity (gCO_2/t km) of new trucks decreased by around 14% from 2019 to 2022, in part due to efficiency measures, operational improvements and an increase in biofuels in the fuel mix.[11] An important qualification is that the overall efficiency improvements from fuels/operational parameters are limited, which makes the case for scaling up innovations and the deployment of zero-emission heavy-duty vehicles whose efficiency credentials are strong.[12]

The increasing availability of electric truck models, as well as their improved range coverage and performance, is opening the door for long-distance transport, resulting in surging sales across markets. In 2024, global electric medium- and heavy-duty trucks sales surpassed 90,000 units (representing a year-on-year growth of 80%). China accounted for 80% of global sales, which has been ascribed to that country's introduction of purchase incentives, a fall in battery prices, and an on-going vehicle scrappage scheme.[13] Within the European Union (EU) approximately 10,000 electric heavy truck units were sold in 2024 (a twelve-fold increase on 2022 when only 820 units were sold) indicating a strong growth in market demand.[14] Increased sales were also observed in the Canada (2,000 units), United States (1,700 units), Japan/South Africa/Thailand (combined 900

6 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025; WEF (2025b). *Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025*. Geneva: World Economic Forum. Available at: https://www.weforum.org/publications/scaling-the-industrial-transition-hard-to-abate-sectors-and-net-zero-progress-in-2025.

7 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

8 IEA (2023b). *World Energy Outlook 2023*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/world-energy-outlook-2023; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

9 ITF and OECD (2022) *Decarbonising Europe's Trucks: How to Minimise Cost Uncertainty*, Available at: https://www.oecd.org/en/publications/decarbonising-europe-s-trucks_ab17c66b-en.html

10 CALSTART (2025); Global Drive to Zero (n.d.-a). Zero-Emission Technology Inventory (ZETI). Available at: https://globaldrivetozero.org/tools/zeti.

11 WEF (2024). *Net-Zero Industry Tracker: 2024 Edition*. Geneva: World Economic Forum. Available at: https://www.weforum.org/publications/net-zero-industry-tracker-2024/downloads-net-zero-tracker-2024, (2025b). *Scaling the Industrial Transition: Hard-to-Abate Sectors and Net-Zero Progress in 2025*. Geneva: World Economic Forum. Available at: https://www.weforum.org/publications/scaling-the-industrial-transition-hard-to-abate-sectors-and-net-zero-progress-in-2025.

12 ITF and OECD (2023). *How governments can bring low-emission trucks to our roads – and fast*. Available at: https://www.oecd.org/en/publications/how-governments-can-bring-low-emission-trucks-to-our-roads-and-fast_80680242-en.html

13 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.

14 ICCT (2025b). *Race to Zero: European Heavy-duty Vehicle Market Development Quarterly (January–December 2024)*. Washington, D.C.: International Council on Clean Transportation. Available at: https://theicct.org/publication/r2z-eu-hdv-market-development-quarterly-jan-dec-2024-feb25.

units) and Brazil (500 units)[15] From a global perspective, a nuance that needs to be recognized is that most of the zero-emission heavy-duty truck deployments are primarily concentrated in closed loop applications, namely, factories, ports, and urban delivery.[16]

In 2024, approximately 70,000 electric buses were sold, representing a year-on-year growth of 30%. This was largely driven by growth in China (70%), Europe (15%) and Latin America (almost 40% of sales outside of China and Europe).[17] China boasts the largest stock of electric buses at 30% (compared to only 2% in the EU), with this share projected to grow.[18] 70% of the current fleet of electric buses deployed by China date to before 2020 and, in 2024, that country's global electric bus exports reached 15,000 units, representing 23% growth on 2023.[19] In the European region, the United Kingdom accounted for 20% of regional electric bus sales in 2024 (with 2,000 units sold), followed by Italy, with approximately 1,200 sales, and Germany, with almost 900 sales – with the important note that a majority of electric buses sold in Europe were for city mobility.[20] In 2024, the Republic of Korea and India also witnessed increases in their national electric bus markets, with sales volumes greater than 3,200 and 2,800 units, respectively.[21] Some of the major players driving electric bus development globally include but are not limited to BYD, Zhongtong, Solaris, MAN, Ebusco, Ashok Leyland, Tata Motors, and Force Motors.[22]

Decarbonization pathways for heavy-duty road transport

With rapid urbanization, especially in emerging and developing economies, it is projected that demand for freight and bus services is likely to increase. Therefore, the rapid deployment of zero-emission heavy-duty vehicles powered by clean energy sources is essential to reducing dependence on fossil fuels. Key drivers that can complement the deployment of sustainable variants include but are not limited to energy efficiency standards to reduce GHG emissions, incentives to improve air quality, and public procurement to generate demand for new, innovative products and services. These drivers can promote climate and societal benefits in parallel across economies, if implemented correctly.

In the short to medium term, the transport sector's carbon footprint can be reduced by introducing and/or complying with stringent efficiency standards for trucks and buses. But, whereas such standards can be ratified in the short term, the effects will not become evident until the medium and long term. For example, the EU's CO_2 emission standard requires heavy-duty fleet manufacturers and operators to achieve a 15% and 45% emission reduction by 2025 and 2030, respectively (compared to 2019–2020 levels). The EU's Vehicle Energy Consumption Calculation Tool (VECTO) is designed to simulate fuel consumption for heavy-duty vehicles.[23] Experts have noted that the EU is largely on track to comply with its emission reduction targets, further driven by efficiency improvements (driveline, aerodynamics, rolling resistance etc.)

To further reduce freight transport energy intensity, rail and shipping should be considered as options. According to IRENA's central models, electrification is an important means of addressing energy demand in scenarios that comply with international efforts to limit global

15 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
16 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
17 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
18 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
19 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
20 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
21 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
22 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
23 Carrilho (2025). "EU CO_2 Emission Standards for Heavy-Duty Vehicles: EU CO_2 Standards for Heavy-Duty Vehicles Set Deep Emission Cuts by 2040". Available at: https://netzerocompare.com/policies/eu-co2-emission-standards-for-heavy-duty-vehicles

warming to 1.5°C. Electrification of end-use sectors (including transport) would need to have reached 30% and 52% by 2030 and 2050, respectively, under these scenarios.[24] By 2030, the share of electrification in the transport sector would need to have increased from 1% to 7%.[25] In regard to heavy-duty vehicles, the International Council on Clean Transportation (ICCT) projects emissions to have peaked in 2025 and decline thereafter, as the sales of zero-emission variants increase alongside robust regulation. The ICCT estimates that 22 billion tonnes of CO_2 emitted cumulatively could be avoided through 2050, if these trends hold true.[26] Significant reduction in energy intensity will require large investments in infrastructure projects, whose impact will take decades to materialize. Renewable road transport options, such as the integration of electric trucks and buses, together with those powered by renewable fuels, can facilitate the transport sector in its aim of becoming a zero-emission sector in the long term.

Several of IRENA's analyses have found electric trucks and buses to be the most attractive option for various reasons: their higher efficiency potential, greater market penetration, and the potential for harnessing broad synergies with battery-electric cars, which are at the forefront of the transport sector's sustainability transformation. Such developments would also lead to a lower total cost of fleet ownership for electric variants.[27] This observation is confirmed by the patent trends for heavy-duty trucks and buses shown in Chapters 2 to 6.

For heavy-duty trucks, the deployment of electric variants is dependent on application, given that some duty cycles are more favorable to electrification. Duty cycles that have a combination of lower daily mileage, low speeds and defined routes are the easiest to electrify, because it is easier to plan charging, and the operator is able to install charging points at strategic locations (e.g., at the site returned to at the end of a delivery).[28] Examples include package delivery, postal delivery and food delivery. Battery-electric trucks are the operational technology most likely to catalyze the decarbonization of this transport mode in the near to medium term.[29]

In regard to buses, electrification is the preferred decarbonization solution. This is because their operation is more predictable compared to heavy-duty trucks, given that schedules and routes are usually fixed, and therefore amenable to depot charging. Moreover, there are battery stocks available in the market that allow buses to complete a full day's service (in an urban duty cycle) relying solely on an overnight charge, while providing a service comparable to their diesel counterparts.[30] Furthermore, bus electrification of buses can be viewed as a great conduit for supporting the adoption of vehicle-to-grid technology. This is because electric bus operators are able to charge vehicles during off peak hours and then feed stored electricity back into the grid at periods of high demand.[31] This concept also applies to the electrification of other road transport categories, namely, passenger cars, heavy-duty trucks and two/three wheelers.

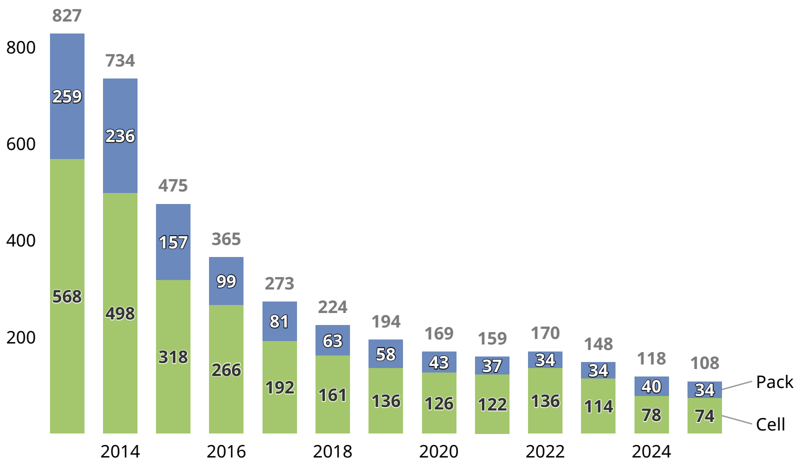
Battery innovation and cost competitiveness are bolstering the case for the electrification of most forms of road transport. Between 2013 and 2025, the weighted average price of lithium-ion (Li-ion) battery packs declined 86% to USD 108 per kilowatt hour (kWh). The cost of Li-ion

24 IRENA (2024a). *Critical Materials: Batteries for Electric Vehicles*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles.
25 IRENA, COP30 and GRA (2025). *Delivering on the UAE Consensus: Tracking Progress Toward Tripling Renewable Energy Capacity and Doubling Energy Efficiency by 2030*. Abu Dhabi: International Renewable Energy Agency, COP30 Presidency and Global Renewables Alliance. Available at: https://www.irena.org/Publications/2025/Oct/UAE-Consensus-2030-tripling-renewables-doubling-efficiency.
26 ICCT (2026). Vision 2050: Update on the global zero-emission vehicle transition in 2025. International Council on Clean Transportation. Available at: https://theicct.org/publication/vision-2050-update-on-the-global-zev-transition-in-2025.
27 ICCT (2026). Vision 2050: Update on the global zero-emission vehicle transition in 2025. International Council on Clean Transportation. Available at: https://theicct.org/publication/vision-2050-update-on-the-global-zev-transition-in-2025; WIPO (2025). *WIPO Technology Trends Report 2025: The Future of Transportation*. Geneva: World Intellectual Property Organization. Available at: https://www.wipo.int/web-publications/wipo-technology-trends-future-of-transportation/en/index.html.
28 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025.
29 IEA (2025a). *Global EV Outlook 2025*. Paris: International Energy Agency. Available at: https://www.iea.org/reports/global-ev-outlook-2025; IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
30 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
31 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

battery cells also fell below USD 74/kWh during the same period.[32] Figure 7.2 shows the Li-ion battery cost competitiveness evolution.

The cost of Li-ion battery packs has declined greatly in recent years

Figure 7.2 Cost of Li-ion battery pack and cell split, volume weighted average (2013–2025)



Note: Historical prices have been updated to reflect real 2025 USD. Weighted average survey value for 2025 includes 320 data points from passenger cars, buses, commercial vehicles, two- and three-wheelers and stationary storage. In EVs, the pack consists of cells, module housing, battery management systems (BMS), wiring, pack housing and thermal management system. For stationary storage, we consider the battery rack, which holds stacked cells, modules, or packs, including the BMS, wiring and the rack housing.

Source: BloombergNEF, 2025.

The energy density of some newly commercialized batteries has crossed the 500 watt-hours per kilogram (Wh/kg) mark and battery chemistry innovations, such as lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP), are increasing application options in the transport sector.[33] A comparative projection of battery energy density and cost is shown visually in Walter *et al.*, 2023.[34]

Continuous innovation in battery design is viewed by the truck and bus industries as the most attractive option to accelerate decarbonization and reduce energy intensity. Battery cost competitiveness will continue to facilitate the widespread adoption of electric variants across regional markets.

While electrification is most certainly the future, there is still a large presence of trucks and buses powered by the internal combustion engine (ICE) that will remain in operation over the next three decades and will need phasing out as quickly as possible. Heavy-duty vehicles have lifespans of between 10 and 15 years, with some extending beyond 20 years, thus emphasizing the need for quick win solutions. One avenue toward reducing emissions from current ICE heavy-duty vehicles is the greater use of biomass-based substitutes in the short to medium term. Biofuel blending is the dominant policy option besides electrification for decarbonizing road transport (currently about 50 countries have regulations regarding biofuel blending).[35] Fleet refurbishment cycles and end-of-life management are two of the most cost-effective actions toward zero-emission replacement.

32 BloombergNEF (2025). Lithium-ion battery pack prices fall to $108 per kilowatt-hour, despite rising metal prices: BloombergNEF. Available at: https://about.bnef.com/insights/clean-transport/lithium-ion-battery-pack-prices-fall-to-108-per-kilowatt-hour-despite-rising-metal-prices-bloombergnef; IRENA (2024c). *Critical materials: Batteries for electric vehicles*, Abu Dhabi: International Renewable Energy Agency. Available at: www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles

33 IRENA (2024c). *Critical materials: Batteries for electric vehicles*, Abu Dhabi: International Renewable Energy Agency. Available at: www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles

34 See page 4Walter, D., *et al.* (2023), X-Change: Batteries — The Battery Domino Effect, Rocky Mountain Institute, Basalt. Available at: https://rmi.org/wp-content/uploads/dlm_uploads/2023/12/xchange_batteries_the_battery_domino_effect.pdf

35 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.

In the long run, sustainable biomass usage should be prioritized when the application of electrification and other low-carbon alternatives is limited.

Beyond biomass, the use of hydrogen to power heavy-duty vehicles is being explored. According to the Global Drive to Zero platform, there were 68 hydrogen-powered heavy-duty vehicle models in service in 2026 (heavy-duty trucks, coaches, school buses, shuttle buses, and transit buses), up from 27 models in 2021. While the patent trends described previously demonstrate that innovation is happening in this space, the economics and learning curves of vehicles such as these lag far behind those of electric trucks and buses – thereby impacting their technical development. Renewable-based hydrogen could be prioritized in those sectors where the impact for decarbonization is significant, however, this is not truly applicable to heavy-duty road transport. There are cases where hydrogen-powered trucks (fuel cell variants) could be considered advantageous when ranges extend over 800 kms.[36] Hydrogen is currently being explored for decarbonization in the production of ammonia, steel and synthetic fuels for long-haul aviation and shipping.[37]

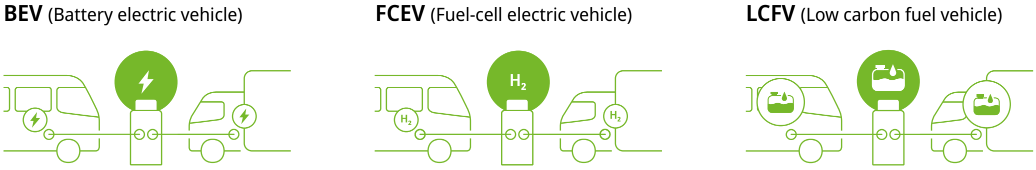
The decarbonization pathways available for heavy-duty trucks and buses are as follows, and are also summarized in Figure 7.3:

- CO_2 emissions reduction can be facilitated by robust efficiency and emissions standards mandated by national laws. Where there is strong demand for freight services there could be benefits beyond increased efficiency, by ensuring adequate sustainable infrastructure is available and/or moving toward rail transport, which can reduce energy intensity.
- Battery-electric trucks and buses are the key driving force for decarbonization of the heavy-duty road transport sector. The cost competitiveness of batteries, as well as higher system efficiency (well-to-wheel), is the main reason for this trend. Focus now needs to be on the rapid deployment of charging infrastructure.
- In the short-to-medium term, sustainable biofuels can be used to power ICE fleets, which should eventually be phased out to ensure a complete decarbonization of the sector.
- Hydrogen-powered trucks and buses are an option; however, the economics argue against their suitability compared to battery-electric options. For hydrogen variants to reach scale there is a need for immediate massive infrastructure investments. This does, however, represent a risk, as battery-electric variants are currently the most competitive models attracting the greatest interest from investors. This could make current H_2 transport infrastructure investments debatable due to potential under utilization.
- Key infrastructure needs for electric heavy-duty trucks and buses:
  - Development frameworks to facilitate to rapid permitting for infrastructure projects, as well as interoperable standards for OEM components;
  - Fast-charging infrastructure, with slow charging offered at depots;
  - Expansion of new distribution grids and reinforcement of existing infrastructure;
  - Digital solutions for smart charging;
  - Battery-swapping facilities;
  - Provision of storage options at charging stations to reduce peak loads.

36 Qurik (2024). "Do hydrogen-powered trucks have a future?”. Available at: https://www.gridserve.com/do-hydrogen-powered-trucks-have-a-future/
37 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: international Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.

Battery electric, Fuel cells, and sustainable biofuels are technical options available for heavy duty road transportation decarbonization

Figure 7.3 Decarbonization options for heavy-duty vehicles



Source: Zhang *et al.*, 2025.

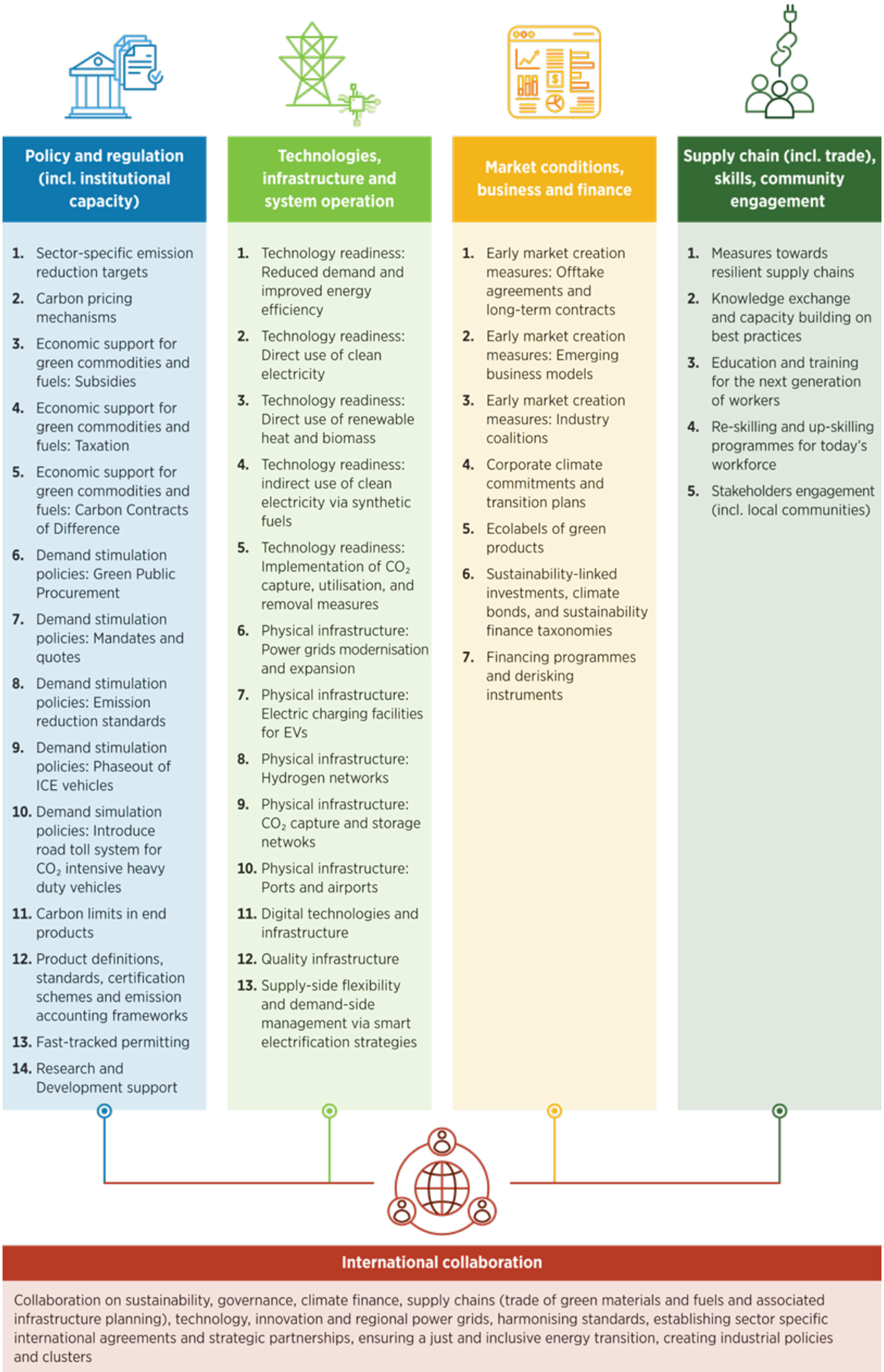
Mapping the enablers and tracking progress toward the decarbonization of the heavy-duty road transport sector

If current plans and policies are to be realized, a fifth of global heavy-duty vehicles sold by 2030 will need to be electric-powered. In the ICCT's Paris 1.5°C compliant scenario, this would need to double to more than 40% of the global total.[38] Such a substantial ambition gap necessitates addressing the multiple barriers to scaling up electric truck and bus adoption. To advance the decarbonization effort of this sector, and to facilitate a clearer understanding of the various enabling conditions, IRENA has applied its systemic innovation approach across five enabling dimensions.[39] To translate these enabling dimensions into actionable insights, IRENA has mapped and organized the necessary actions and initiatives onto 39 "enablers".[40] Grouped into four, these enablers are action-oriented, as well as serving to highlight the instruments and mechanisms necessary to accelerate the sustainable transformation of the transport sector. The "International collaboration" dimension is cross-cutting, emphasizing the need for different actors across geographies to collaborate on enabling activities (Figure 7.4). By identifying and articulating precise enablers, the mapping facilitates targeted planning, fosters coherent policymaking, and supports collaborative efforts among stakeholders. This structured methodology can help ensure that all the essential aspects of hard-to-abate decarbonization are comprehensively addressed.[41]

38 ICCT (2026). Vision 2050: Update on the global zero-emission vehicle transition in 2025. International Council on Clean Transportation. Available at: https://theicct.org/publication/vision-2050-update-on-the-global-zev-transition-in-2025.
39 Systemic innovation – that is, innovation beyond technology – is needed, including holistic enablers in the areas of policy and regulation, physical and digital infrastructure, new market designs, business models, finance, supply chains, skills and capacity building, stakeholder engagement, and international collaboration.
40 IRENA's taxonomy serves as a structured guide, categorizing and clarifying the diverse approaches required to fulfil sector-specific needs effectively.
41 IRENA (2025). Decarbonising hard-to-abate sectors with renewables: Enablers and recommendations. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Decarbonising-hard-to-abate-sectors-with-renewables-Enablers-and-recommendations.

There are several enablers across different dimensions that IRENA has identified to drive decarbonization in hard to abate sectors

Figure 7.4 Hard-to-abate sector decarbonization enablers within the enabling dimensions



Source: IRENA (2025).[42]

42 IRENA (2025). Decarbonising hard-to-abate sectors with renewables: Enablers and recommendations. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/ Decarbonising-hard-to-abate-sectors-with-renewables-Enablers-and-recommendations.

Tracking progress: policies and regulation

Efforts toward the decarbonization of road freight transport have already begun, with wide policy measures and targets in place. Countries are setting quantitative targets for the sales of sustainable and zero-emission vehicles. According to the global "Memorandum of Understanding (MoU) on Zero-Emission Medium- and Heavy-Duty Vehicles", 25 countries have pledged to introduce zero-emission trucks and buses by 2040. The overall ambition for signatories of this MoU is to facilitate the identification of pathways toward accelerating the deployment of zero-emission heavy-duty vehicles and associated infrastructure. The target is to ensure that sales of zero-emission HDV's reach 30% by 2030, so as to enable a full transition to zero-emission medium- and heavy-duty vehicles (ZE-MHDVs) in new fleets by 2040 to facilitate the achievement of net-zero carbon emissions by 2050.[43] Specifically for buses, Costa Rica has pledged to reach 70% electric and fuel cell buses in national fleets by 2040, rising to 100% by 2050, whereas Singapore's National Green Plan 2030 aims to have electrified half its total bus fleet by 2030.[44]

Targets are being announced in developing markets as well. For instance, Rwanda has committed to electrify 10% of all public buses by 2030, and Uganda's 2024 E-Mobility Strategy commits to 100% electrification of buses by 2030.[45] To accelerate the decarbonization of trucks and buses, some governments have also developed plans to completely phase out internal combustion variants in the long term. Ethiopia is another country to have set ambitious electrification targets for the transport sector, such as ensuring that 100% of newly procured government fleet vehicles are electric powered, as well as ensuring that all newly introduced public transport vehicles are electric powered (freight vehicles alone contribute more than 50%, while public transport vehicles with more than 12 seats account for 20% to these emissions).[46] Currently, eight governments have set ambitious ICE truck phase-out targets, aiming for at least 40% of all truck sales to be electric by 2050.[47]

To promote the adoption of zero-emission heavy-duty vehicles, major markets such as Canada, China, the EU, Germany and India, along with several national and regional governments, have begun offering purchase incentives. Major developments are especially evident in India, where, under the EV Scheme FAME I and II, the country has provided subsidies for the purchase of 7,500 electric buses between 2015 and 2024. In 2024, the country announced it would provide an additional USD 396 million in incentives to procure 38,000 electric buses for public use between 2024 and 2029.[48] In addition or apart from direct incentives, many countries have begun offering fiscal support, such as tax benefits or credits, to increase the market penetration of electric trucks. Benefits vary widely across countries, however. For instance, the Netherlands has introduced a truck fossil fuel levy of EUR 0.17/km that is expected to generate revenue totaling EUR 1.6 billion from 2026 to 2030.[49] It is expected that EUR 980 million of this revenue will be invested into developing purchase subsides for zero-emission trucks. China's current 10% purchase tax waiver for energy efficient vehicles (battery-electric, plug-in hybrid, fuel cell-electric) is now applicable to trucks. For new vehicles purchased during 2026–2027, tax will be reduced by 50% and exemptions reach up to 15,000 Chinese yuan. This program is a pioneer in the heavy-duty road transport segment, aiming to bolster net-zero supply chains, encourage fleet electrification, and provide manufacturing certainty for domestic OEMs.[50]

43 Global Drive to Zero (n.d.-a). Zero-Emission Technology Inventory (ZETI). Available at: https://globaldrivetozero.org/tools/zeti.
44 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
45 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
46 Federal Republic of Ethiopia (2025). *Ethiopia E-Mobility Strategy and Implementation Plan 2025-2030*. Available at: https://www.motl.gov.et/sites/default/files/resource/V4_Oct%2010_E-mobility%20Strategy%20and%20Implementation%20Plan.pdf
47 ICCT (2024). Zero-emission vehicle phase-ins: Medium- and heavy-duty trucks (February 2024). International Council on Clean Transportation. Available at: https://theicct.org/zero-emission-vehicle-phase-ins-medium-and-heavy-duty-trucks-feb24.
48 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
49 Government of the Netherlands (2024). "Vrachtwagenheffing levert €1,6 miljard op voor verduurzaming en innovatie". Available at: https://www.rijksoverheid.nl/actueel/nieuws/2024/10/04/vrachtwagenheffing-levert-%E2%82%AC16-miljard-op-voor-verduurzaming-en-innovatie
50 Xinhua (2023). "China extends preferential purchase tax policy for NEVs", Available at: https://www.chinatax.gov.cn/eng/c101269/c5205697/content.html

Another financial tool that can be considered is residual value guarantees. Such a framework guarantees a minimum resale value for sustainable heavy-duty vehicles at the end of the leasing/financing term. This is particularly relevant for those technologies that are still at the early stage and/or where the market value of used vehicles is non-existent.[51]

Green public procurement legislation should be explored and governments lead guidance to facilitate the implementation of procurement principles. For example, the EU's Clean and Energy-Efficient Road Transport Vehicles Directive stipulates that, when making purchasing decisions, consumer and businesses must take into consideration such factors as energy consumption, CO_2 emissions and hazardous pollutants, so as to contribute to the bloc's overall efforts to decarbonize the transport sector. In the case of electric buses, in Singapore, the government has taken the responsibility of covering all the costs associated with electric bus procurement. In 2023, it provided USD 124.3 million for the procurement of 360 electric buses and USD 34.4 million for the purchase of charging infrastructure at three bus depots.[52]

Different economies are exploring the development and implementation of green public procurement legislation and guidance to support the implementation of sustainable procurement principles. This requires businesses and consumers to take into consideration such variables as energy consumption and hazardous pollutants in purchasing decisions, with the intention of making the bloc's transport sector more sustainable.

Regulatory instruments, particularly standards for emissions reduction, are widely used by governments across economies to limit vehicle emissions. Such standards apply to CO_2 and other greenhouse gases. A prominent example is the EU, where new CO_2 emission standards have been introduced that set a 45% emissions reduction target for heavy-duty vehicles by 2030 compared to 2019 levels, increasing to 90% by 2040.[53] Other major economies, such as Canada, China, India, Japan and the United States, apply similar standards to heavy-duty vehicles.[54]

In the gradual phase-out of direct economic support measures for heavy-duty vehicle segments, adequate carbon pricing is pivotal to ensuring a level playing field and accelerating the shift to zero-emission vehicles. Germany's revamped tolling system (Eurovignette) started in 2023, whereby trucks pay a CO_2 surcharge (EUR 200/tCO_2). Zero-emission trucks fall into the lowest emission class and incur no surcharge. In the Netherlands, zero-emission zones have proved to be a very powerful tool in promoting the deployment of electric heavy-duty vehicle (e-HDV) sales. Electric truck sales in the country grew by 188% in the first half of 2025, far outpacing the European average of 46%.[55]

Tracking progress: technology, infrastructure and system operation

Emerging charging options are being explored by the transport industry to catalyze the electrification of heavy-duty vehicles. While there is an intense focus on developing overnight charging capacities for such vehicles, there is also a great deal of innovation going into developing rapid charging options to empower fleet operators in increasing the share of e-HDVs in their fleets – especially for regional and long-haul operations.[56] There is also significant research ongoing into optimizing charging infrastructure networks to install confidence into fleet operators in using long-haul electric trucking across several geographies. Innovations such as megawatt-scale charging systems to allow for ultra-fast charging on long distance travel are

51 ITF and OECD (2025). *Financing the Electrification of Heavy-Duty Vehicles*. Available at: https://www.itf-oecd.org/sites/default/files/docs/financing-electrification-heavy-duty-vehicles.pdf
52 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
53 EC (2023b). Reducing CO_2 emissions from heavy-duty vehicles. European Commission. Available at: https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en (accessed 10 January 2024).
54 The Climate Change Authority (2023). International implementation of vehicle emissions standards. The Climate Change Authority of Australia. Available at: https://www.climatechangeauthority.gov.au/reviews/light-vehicle-emissions-standards-australia/international-implementation-vehicle-emissions.
55 Clean Cities (2025) "Dutch courage pays off: zero-emission zones spark rapid uptake of electric vans and trucks", Available at: https://cleancitiescampaign.org/dutch-courage-pays-off-zero-emission-zones-spark-rapid-uptake-of-electric-vans-and-trucks/; ITF *et al*. (2025) *Financing the Electrification of Heavy-Duty Vehicles*, Available at: https://www.itf-oecd.org/sites/default/files/docs/financing-electrification-heavy-duty-vehicles.pdf.
56 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.

gaining traction.[57] A partnership between Daimler, Volvo and Traton Group is aiming to deploy 1,700 ultrafast charging points for trucks and buses across Europe.[58] Megawatt charging is also due to be rolled out in the United States in 2026 and 2027, largely through the introduction of the Tesla Semi.[59]

Several regional charging standards for heavy-duty trucks are under development and likely to be adopted internationally. In 2022, CharIN introduced the Megawatt Charging Standard that had 3.75 MW as a maximum power rating. The Standard was scheduled for adoption in 2024 in several regions globally,[60] and is gaining traction across markets in Asia and Europe. More recently, in 2023, China established the ChaoJi charging standard, which has a maximum power rating of 1.2 MW.[61]

Across economies there are dedicated policies focused on the deployment of charging infrastructure for heavy-duty vehicles. Emerging initiatives being spotlighted include the development of charging corridors, as well as an increase in the provisions of grants and subsidies directed at charging points. Europe is a leader on the policy and charging infrastructure side, as evidenced by the establishment of the Alternative Fuels Infrastructure Regulation (AFIR), with the objective of installing electric recharging stations with a minimum output of 350 kW for heavy-duty vehicles along the Trans-European Transport Network by 2030.[62] The EU's European Clean Transport Corridor initiative aims to support charging corridor development by easing and streamlining permits for charging point deployment. An ICCT study estimates that by 2030 the EU will require between 22 and 28 gigawatts (GW) of installed charging power capacity in order to support the electrification of its truck fleet. This entails the installation of 150,000–175,000 private chargers and 60,000–80,000 public chargers across the region. This same study finds that the 350 kW chargers have the potential to cover more than 50% of public fast charging needs for long-haul trucks, and AFIR is expected to cover between 50–70% of public charging needs.[63]

Advanced power system planning and grid management measures are being used to better understand charging requirements, while also catalyzing heavy-duty vehicle electrification. The introduction of storage capacity and the development of renewable energy corridors are viewed as significant enablers that complement the development of charging infrastructure corridors. Smart charging options can contribute toward grid cost reductions for infrastructure and electricity procurement. Power system flexibility is being enhanced by increasing the integration of vehicle-to-grid (V2G) technology by enabling electric trucks and buses to not only to draw power from the grid, but also supply electricity back to it (as a distributed storage asset). This can enhance grid stability, as well as offer potential new revenue streams for electric fleet operators.[64] Smart charging measures have already been adopted in the United Kingdom (which mandated compliance with its Open Charge Point Protocol in 2022), as well as in Belgium and Luxembourg[65] – demonstrating that charge point operators can play a critical role in grid balancing by engaging in flexibility markets. Advanced planning tools such as EPRI (European

57 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
58 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
59 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
60 CharIN (2022). *CharIN Whitepaper Megawatt Charging System (MCS): Recommendations and Requirements for MCS Related Standards Bodies and Solution Suppliers*. Berlin: Charging Interface Initiative. Available at: https://www.charin.global/technology/mcs.
61 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
62 EC (2023a). Alternative fuels infrastructure: Council adopts new law for more recharging and refuelling stations across Europe. European Council. Available at: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/alternative-fuels-infrastructure-council-adopts-new-law-for-more-recharging-and-refuelling-stations-across-europe.
63 ICCT (2025b). *Charging infrastructure needs for battery electric trucks in the European Union by 2030*, Berlin, Germany. Available at: https://theicct.org/wp-content/uploads/2025/10/ID-476-%E2%80%93-EU-BETs_report_final-1.pdf
64 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
65 IRENA (2023). *Innovation Landscape for Smart Electrification: Decarbonising End-use Sectors with Renewable Power.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2023/Jun/Innovation-landscape-for-smart-electrification.

Power Research Institute)'s GridFAST[66] can help fleets connected more quickly and cost effectively to the grid. EPRI's eRoadMAP[67] helps regulators approve utility investment ahead of time in freight corridors and other places of future transport electrification demand.

Tracking progress: market conditions, business models and finance

Many heavy-duty vehicle manufacturers are prioritizing the decarbonization of fleets by setting ambitious electrification targets. Daimler Truck expects up to 60% of its European sales to come from EVs by 2030, while Volvo wants 50% of all global sales to be electric within the same time frame.[68] Several other market players, such as Maersk, Sysco, Holcim, Schneider National, and Rio Tinto, have placed orders for heavy-duty electric trucks from Daimler, Volvo, Scania and others. There is a strong consensus regarding a transition to zero-emissions vehicles – around 4,000 companies globally have committed to science-based targets, with several actively seeking zero-emission trucks backed by a willingness to pay a premium for them.[69]

Industry initiatives have a significant potential to accelerate efforts toward the decarbonization of trucks and buses. Notable examples are the Road Freight Zero and the Smart Freight Centre's Fleet Electrification Coalition, which are focusing demand aggregation of electric trucks to bypass the challenges associated with charging infrastructure. These initiatives are also exploring the development of innovative financing solutions for zero-emission trucks.[70]

New business models are being introduced to tackle the high upfront costs associated with e-HDVs.

- "Mobility as a service" is a business model applicable to buses and heavy-duty trucks, whereby transport operators can lease a transport modal for a defined period of time. For example, in India, this model is being used by state public transport operators to procure electric buses from manufacturers under a 12-year fixed-contract agreement. This framework allows bus operators to bypass the associated financial and fiscal risks that they would otherwise have to bear if they were to approach a manufacturer independently.[71]
- "Pay-as-you-drive" (buses) is another business model in which transport companies can purchase an electric vehicle at a comparable cost to its diesel variant and participate in a subscription scheme. The subscription cost covers leasing the electric vehicle battery, charging services and overall vehicle maintenance.[72] Scania has its own pay-per-use model providing clients with easier access to electric truck solutions and incentivizing companies to make the switch by eliminating the high upfront costs for adoption.[73]
- Broad leasing of zero-emission trucks and buses is also an effective business model that encourages uptake. The advantage of this model is that operators pay according to usage, thereby bypassing any upfront capital expenditure. The maintenance and depreciation risks are borne by the leasing company, encouraging operators to accelerate the integration of zero-emission variants into their fleets. For example, companies like WattEV (US-based) act as demand aggregators, purchasing e-trucks from manufacturers such as Volvo, BYD, and Tesla, capitalizing on available incentives and offering leasing options to carriers and shippers.[74]

66 See, https://www.gridfast.com/about.
67 See, https://eroadmap.epri.com.
68 Soulopoulos, N. (2023). Volvo, VW and Daimler better get a move on with electric trucks. Bloomberg.com. Available at: https://www.bloomberg.com/news/newsletters/2023-08-22/volvo-vw-and-daimler-better-get-a-move-on-with-electric-trucks.
69 MCFM (2022). Preparing the world for zero-emission trucks. McKinsey Center for Future Mobility, McKinsey & Company. Available at: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/preparing-the-world-for-zero-emission-trucks.
70 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
71 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
72 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
73 Scania (2023). Scania and sennder establish JUNA, a joint venture to drive large-scale electric truck adoption and accelerate decarbonisation of European road logistics. Available at: https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/4675185-scania-and-sennder-establish-juna--a-joint-venture-to-drive-large-scale-electric-truck-adoption-and-.
74 ITF *et al*. (2025). *Financing the Electrification of   Heavy-Duty Vehicles*, Available at: https://www.itf-oecd.org/sites/default/files/docs/financing-electrification-heavy-duty-vehicles.pdf.

- Battery-swapping is a potential model for enabling the efficient and cost-effective operation of electric trucks, given the rapid swap time. This model has not, however, gained widespread adoption due to the limited market penetration of electric trucks. This business model would also require the greater standardization of battery technologies and charging processes. One advantage of this model is the ability it gives to charge batteries in optimal conditions at swapping stations. Allowing batteries to be charged at off-peak times can support the power system flexibility of electrical grids.[75] China currently leads the world in the deployment of battery-swapping infrastructure for heavy-duty trucks. Although upfront infrastructure costs, appropriate skills development and technical standardization remain challenges, battery-swapping has become a commercially viable solution in high-utilization, fixed-route freight segments, positioning China at the forefront of heavy-duty road transport electrification.
- Fleet management is another conduit for supporting the deployment of electric alternatives to heavy-duty trucks and buses. Analyzing factors such as vehicle use, route length and charging infrastructure availability can serve to inform bus and truck operators when determining the best vehicle technology to deploy for different routes. By including fleet management in policies, there is an opportunity to facilitate the adoption of electric heavy-duty trucks and buses.[76]
- Utility-led process improvements such as GridFAST, which decrease costs and speed up interconnection for fleets, and eRoadMAP, which confidentially shares a fleet's electrification plans with utility regulators and grid planners to swiftly and cost-effectively upgrade the grid when and where needed, are two examples of tools connecting power system operators with fleet operators.

If financing and de-risking instruments are leveraged correctly, they can greatly catalyze the deployment of zero-emission heavy-duty vehicles. Several multilateral banks are supporting the introduction of sustainable trucks and buses. In 2024, the World Bank started financing loans to support the procurement of electric buses, as well as chargers and maintenance services, in Cairo.[77] In 2023, the African Development Bank allocated USD 1 million toward a technical assistance grant through its Sustainable Energy Fund for Africa to the Green Mobility Facility for Africa. This was aimed at accelerating private investment in sustainable transport solutions in seven countries (Kenya, Morocco, Nigeria, Rwanda, Senegal, Sierra Leone and South Africa) by creating supportive business models and enabling environments for electric mobility.[78] In 2025, Milence (a Netherlands-based charging company) received a grant of USD 125 million from the EU to build electric truck charging infrastructure at 71 locations across 10 EU Member States.[79] Regional blocs can also develop mechanisms and initiatives to attract financing for transport decarbonization solutions – with the EU being a model to follow. The EU's Climate Taxonomy Delegated Acts provide a definition of "low-emission heavy-duty vehicles" that makes them eligible for investments or incentives classified as "sustainable" under the EU Taxonomy.[80] The EU's Social Climate Fund is another mechanism offering investments that contribute toward the broad reduction of emissions from the road transport sector. The EU's Innovation Fund has a strong track record of offering financing toward battery technologies and zero-emission vehicle solutions. National policies and frameworks are also effective in driving sectoral change. For example, in the Netherlands, starting from 2026, domestic and international trucks will pay a truck toll for using national roads. This toll applies to trucks weighing more than 3,500 kg and will on average work out at EUR 0.167/km driven (2023 price level). The cleaner and lighter the truck, the lower the toll – thereby incentivizing the adoption of zero-emission variants.[81]

75 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
76 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
77 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
78 AfDB (2023). "$1 million: Sustainable Energy Fund for Africa grant to drive electric mobility shift in seven African countries". Available at: https://www.afdb.org/en/news-and-events/press-releases/1-million-sustainable-energy-fund-africa-grant-drive-electric-mobility-shift-seven-african-countries-58650
79 IRENA (2025). *Policies for Advancing the Renewables-based Electrification of Road Transport*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2025/Jun/Policies-for-advancing-the-renewables-based-electrification-of-road-transport.
80 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
81 Government of the Netherlands (2024). "Vrachtwagenheffing levert €1,6 miljard op voor verduurzaming en innovatie". Available at: https://www.rijksoverheid.nl/actueel/nieuws/2024/10/04/vrachtwagenheffing-levert-%E2%82%AC16-miljard-op-voor-verduurzaming-en-innovatie

Supply chain, skills and stakeholder engagement

Multilateral and international organizations play a critical role in helping industry and community stakeholders identify ways to make the transport sector sustainable. Electrification is gaining significant interest in the dialogue between industry and community stakeholders. IRENA's Collaborative Frameworks (CF) offer a platform that allows Member States to interact with the public and private sectors and discuss how to accelerate the energy transition. The transport sector is prominently featured in the Collaborative Frameworks focusing on Just and Inclusive Transition, Critical Materials, Green Hydrogen, and Geopolitics.[82] Another IRENA initiative concerned with electrification is the Utilities for Net Zero Alliance (UNEZA), an "international platform for co-operation within the power and utilities sector, to address and overcome the common barriers hindering the achievement of emissions reduction targets and the realization of global net-zero ambitions."[83] The Heavy-Duty Vehicles and Engines Hub within the Climate and Clean Air Coalition is another example of an industry-led initiative that facilitates the exchange of best practices and provides access to technical expertise for heavy-duty vehicles. The Hub brings together different stakeholders to accelerate a reduction in carbon emissions through the robust adoption of cleaner fuels and vehicle emission standards.[84]

To support the deployment of electric trucks and buses, governments and industry players are allocating resources and developing upskilling programs for the existing workforce, as well as developing initiatives to attract new talent across several regions. This is essential primarily for the installation and maintenance of charging infrastructure, fleet operations optimization, servicing and EV recycling. The US Environmental Protection Agency's Clean Heavy-Duty Vehicles Program offers grants to organizations that want to train their workforce in the maintenance of new vehicle types, as well as undertake charging infrastructure installation certification under the Electric Vehicle Infrastructure Training Program.[85]

Despite the progress across the various enabling dimensions discussed above, the current pace of adoption of electric trucks and buses is slower than what is needed to achieve Paris Agreement-aligned climate targets. Under IRENA's 1.5°C scenario, EVs should comprise nearly two-thirds of the heavy-duty vehicle stock by 2050.[86] To meet this target, electric variants would need to have become widely available and sold in significant volumes in most jurisdictions around the world this decade. Some of the key barriers to address include high upfront costs, the limited availability of charging infrastructure, a concentration within supply chains, and disparities in electricity taxation relative to fossil fuels.

This section has considered the progress of the heavy duty transportation – trucks and buses – in terms of the enablers mapped by IRENA across each of the enabling dimensions, as well as highlighting the bottlenecks in this sector.

The following sections list the key actions that governments and industry stakeholders could implement to foster the deployment of zero emission trucks and buses, while also contributing to the achievement of broader national and global climate targets.[87]

82 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
83 See, www.utilitiesfornetzero.org.
84 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
85 IRENA (2024b). *Decarbonising Hard-to-Abate Sectors with Renewables: Perspectives for the G7.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Apr/Decarbonising-hard-to-abate-sectors-with-renewables-Perspectives-for-the-G7.
86 IRENA (2023). *Innovation Landscape for Smart Electrification: Decarbonising End-use Sectors with Renewable Power.* Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2023/Jun/Innovation-landscape-for-smart-electrification.
87 This chapter has been prepared by IRENA. The analysis, perspectives and policy recommendations presented are those of IRENA and are not intended to represent the views of the WIPO Secretariat or its Member States.

Reflections and recommendations to accelerate the transition

Reflections on the WIPO and IRENA analysis

WIPO and IRENA have leveraged patent data, and technological and market trends, to highlight net-zero trends in the heavy-duty truck and bus transport segments. Operators using trucks and buses to meet freight and passenger requirements face two major challenges: the implementation of decarbonization solutions and driver shortages. Digitalization offers an opportunity to address both challenges, though it also poses a threat, since the industry is heavily paperwork-reliant worldwide. These pressures are pushing the road transport industry to revolutionize its operation in a shift away from the thoughtful evolution of incremental optimizations that has defined current practices. Road transport is the backbone of modern economies, with any operational disruption representing a significant market risk.

The concepts that will define the adoption of sustainable trucks and buses to meet economic and client needs are the total cost of ownership and capacity. The major bottleneck is one related to the total cost of ownership (TCO) – namely, capacity pairing.

While the TCO of zero-emission vehicles is sometimes lower than for diesel vehicles during first ownership, their higher retail prices require companies to mobilize greater capital, thereby delaying the transition. This is particularly difficult when freight rates are expected to remain constant across powertrains, and interest and insurance rates remain high, and questions about zero-emission vehicle residual values create uncertainty for banks with regard to the financing of the transition.

Regarding capacity, zero-emission vehicles can only operate if they have access to energy. Public infrastructure remains too weak, is poorly adapted to heavy-goods vehicle dimensions and weights, and too expensive to create a favorable TCO. Private infrastructure is growing stronger, but carriers still experience significant delays in setting up depot chargers and accessing a grid that has adequate power. Moreover, private infrastructure is limited to operating the shorter range of zero-emission vehicles, making long-range and international operations difficult without partnerships.

The crucial question to be answered is “Will there be a vehicle available at the right place and time, and at the right price?” The analysis conducted in this report demonstrates that technological innovations are gaining both traction and interest across several markets. Fossil fuel-powered vehicles have set a strong benchmark for zero- and low-carbon technologies to replicate and meet going forward. Global transport operators are evaluating the carbon reduction potential of greener energies with pragmatism.

This joint analysis by IRENA and WIPO shows that the decarbonization of heavy-duty vehicles will leverage a combination of greener powertrains and greater operational efficiency. The most anticipated solutions focus on electrification, given the rapid advancements being made in this area. Biofuels, carbon-neutral fuels, and hydrogen are alternative decarbonization pathways, with varying degrees of expectation. From an efficiency point of view, efforts are focused on improving driver performance, improving fleet efficiency through more energy-efficient vehicles replacing older ones, and more efficient logistics to reduce the number of empty miles and increase vehicle occupancy rates. The adoption and integration of new digital technologies can help in better understanding current operations before optimizing them, and in facilitating communication among multiple stakeholders. This deeper understanding will maximize the potential of existing technologies and practices to lower carbon emissions – the potential for efficiency-driven decarbonization is enormous.

Recommendations

Accelerating sustainability efforts within the heavy-duty road transport sector is a conduit that can greatly contribute toward the decarbonization of the global transport industry. This in turn can have positive spillover effects on other aspects of the energy transition. Considering the analysis and perspective that have been presented in the report thus far, an overview of targeted and actionable recommendations to decarbonize heavy-duty vehicle under each enabler is presented below. These recommendations are presented for the consideration of policymakers, transport associations, and industry representatives in pursuit of effective policy and financial frameworks for this category of transport.

Policy and regulations

A supportive policy environment is required in order to accelerate massive investments into technology and infrastructure for heavy-duty vehicles in the coming decades. A robust regulatory framework is crucial in order to give developers and investors the confidence to make final investment decisions based on clear, stable and credible decarbonization objectives.

- **Recommendation: Establish specific and binding decarbonization targets able to accelerate and complement policy initiatives for green public procurement and fiscal support.**
  - Governments are in the best position and have most capacity to catalyze decarbonization of the heavy-duty road transport sector by setting long term and specific targets. Such targets should be discussed and formulated together with private stakeholders and industry associations. Targets, when reflected in government policy and legislation, are an important tool for signaling intent. They give technology providers and investors the confidence to accelerate innovation activities in regard to sustainable transport and facilitate the introduction of new products and services to existing markets. Targets backed by scenarios and plans can be useful in highlighting compatibility with other sectors and trade-offs in order to secure more buy-in for targets and policy initiatives.
  - Public procurement of sustainable transport options where public and state-owned enterprises purchase goods and services from the private sector can ensure competitive pricing, as well as accelerate the deployment of solutions at scale. Such initiatives can also drive tangible progress toward achieving transport decarbonization targets. Notable initiatives such as the EU's Clean and Energy-Efficient Road Transport Vehicles Directive, as well as Singapore's investments into expanding public electric bus fleets, are examples demonstrating the importance and benefits of public procurement. Another untapped opportunity lies in public tenders for products or services requiring heavy-duty road transport and logistics.
  - Robust policy and regulatory frameworks can allow greater access to finance, which is a catalyst toward the adoption of sustainable trucks and buses. The combination of government subsidies with the aggregation of sustainable truck and bus procurement can further reduce upfront costs – as has been proven for electric variants. Active efforts by governments to ensure that sustainable trucks and buses are eligible for reductions in taxes or tariffs is another enabler to drive adoption of these models. Ireland's Zero Emission Heavy-duty Vehicle Purchase Grant Scheme and India's Faster Adoption and Manufacturing of Hybrid and Electric Vehicles are examples of how governments can address fiscal barriers to the adoption of zero-emission vehicles.

Technology and infrastructure

The development of resilient and diverse renewable energy supply chains is a key pillar of transport sector decarbonization. Economies are increasingly requiring a scale-up in renewable power generation capacity to cater either to direct electrification or produce green hydrogen/clean synthetic fuels. The latest IRENA analysis has found that, in 2025, a record 692 GW of capacity was installed, but that this needs to reach 1,043 GW per year to comply with a 1.5°C scenario. Furthermore, there is a strong impetus toward a scale-up in investments into power grids and enabling infrastructure at all levels (i.e., in transmission and distribution, including EV charging infrastructure), which can accelerate the application of smart electrification strategies to transport and power grids.

- **Recommendation: Catalyze the deployment of critical infrastructure and innovative technologies. There should also be priority given to ancillary considerations such as standardization and accelerated permitting.**
  - Governments can support transition in the transport sector by strengthening cross-sectoral infrastructure planning and international coordination in the deployment of fast charging public infrastructure (MW scale), storage depots, battery swap facilities, and sustainable fuel terminals. Fleets could also confidentially share 1–5-year planning data with utilities and regulatory bodies to the cost-effective upgrade of the grid at critical locations and during the time needed.
  - Multilateral development banks can support the financing of zero-emission vehicles by offering concessional loans in cooperation with public transport authorities and national development banks. Working with the private sector to establish mechanisms for providing funding can facilitate the uptake of zero-emission heavy-duty vehicles. Leasing companies could also serve as intermediaries for receipt of the funding and in so doing act as demand aggregators.
  - Along with the deployment of critical infrastructure to power sustainable truck and bus variants, there is also a requirement to standardize the common design and operational requirements of ancillary infrastructure assets to ensure harmonization and broader market access to products and services across geographies. This is particularly true in regard to the infrastructure requirements for electric trucks and buses, whose charger and charging systems are not standardized. The design of these two crucial components is currently driven by individual manufacturers and thus could hamper the large-scale adoption of electric trucks and buses.
  - Electrification is the leading decarbonization pathway for heavy-duty vehicles (as confirmed by patent data trends). There should therefore be an emphasis on more research and innovation into new battery chemistries, such as lithium ferro phosphate, lithium manganese iron phosphate and sodium-ion batteries, which all have higher energy capacity and lifecycle stability when compared to current technologies available. There is also new and efficient charging infrastructure (such as MW chargers) that should continue to be deployed at strategic locations to maximize route efficiency for trucks and buses. Governments should provide regulatory and financial support to boost research and development in these technologies.
  - Besides regulatory and financial, the development of national and regional capacity/ ecosystems for research (e.g., institutions such as NREL, EPRI, Fraunhofer, CSIRO) is crucial in supporting the identification and deployment of green innovations into markets.

Business models

Decarbonization of the heavy-duty road transport sector offers new business opportunities to private and industry stakeholders. Some options gaining in popularity include pay-as-you-go, truck-as-a-service, battery-as-a-service, and fleet aggregation. These business models offer economic benefits across different strata of society, facilitating a just and inclusive transition.

- **Recommendation: Develop new initiatives designed to spotlight green alternatives for heavy-duty trucks and buses. These initiatives should also catalyze new business models.**
  - Governments can work together with the private sector and industry to develop targeted programs designed to increase the market share of sustainable transport

products and services. For small fleet operators, focusing on demand aggregation initiatives can support positive market initiatives, as well as enable government and industrial actors to collaborate in shaping manufacture. For example, the Global Drive to Zero coalition is an international initiative that works with governments and industry leaders to promote the adoption of zero-emission vehicles, particularly buses and trucks.
- Government and private sector players should explore the development of new business models to facilitate the adoption of sustainable trucks and buses. One example is "mobility as a service", a model wherein state operators purchase vehicle fleets that are then offered as a service to operators, thereby reducing financial risks. Another popular option is "pay as you drive" wherein companies acquire vehicles at a cost comparable to diesel variants. Companies can then charge operators a subscription fee based on kilometers driven.
- Battery-swapping is a potential business model that can support the increased electrification of trucks and buses. The availability of optimally-charged batteries at dedicated depots is the core business mechanic of this model, and can address the challenge of the long charging time required by the batteries for these vehicles. Furthermore, the standardization of battery design and chargers will be a crucial enabler supporting the development of a battery-swapping business model.

Supply chains and skills development

As the heavy-duty road transport sector continues its journey toward phasing out legacy fossil-based technologies and replacing them with green technologies, it is inevitable that global, regional and national transport supply chains will need to be reimagined and made more resilient. The technologies that underpin this sustainable transition rely on different parameters, the most crucial of which is access to critical minerals. Hence, ensuring supply chains are equitable rather than monopolistic will be crucial as this shift continues. There will also be a concurrent requirement for the development of a skilled workforce able to manufacture and utilize innovations to their full potential.

- **Recommendation: Facilitate international collaboration, as well as the development of a skilled global workforce.**
  - Strategic alliances and South–South cooperation will be crucial in addressing technical and economic barriers, as well as in enabling a more rapid deployment of new green transport projects and initiatives. Countries can work together to accelerate an international convergence in definitions, standards, thresholds and certification procedures to enable the international trade of these technologies.[88] Maximizing international collaboration is also crucial if technology monopolization is to be avoided, as well as the introduction of resilience/alternative mechanics into the new supply chains that will likely emerge.
  - Government will need to play a leading and convening role in the development of the knowledge and skills necessary to facilitate the transition for heavy-duty vehicles. Key activities for government to facilitate include exchange of the latest innovations together with guiding financial resources toward the development of specialized educational programs and training.
  - There is a growing necessity to adopt a multilateral collaborative approach, with leaders from national governments, international organizations, industry stakeholders and educational institutions working together to foster a world-class global workforce in the transport sector. The development and availability of specialized laboratories and institutions for the conducting of research and innovation activities in this area would also be a useful complement to skills development programs.

88 IRENA (2024d). *Global Trade in Green Hydrogen Derivatives: Trends in Regulation, Standardisation and Certification*. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/Publications/2024/Oct/Global-trade-in-green-hydrogen-derivatives-Trends-in-regulation-standardisation-and-certification.

Thibault Villien de Gabiole, Lead, Industry Decarbonization – Trucking, World Economic Forum

Deployment pathways for zero-emission trucks

In 2025, the World Economic Forum's First Movers Coalition, in collaboration with Deloitte, interviewed several logistics providers who highlighted that the decarbonization of medium- and heavy-duty trucking – responsible for around 5% of global CO_2 emissions – sits at the intersection of technology progress, infrastructure readiness and capital deployment. [89]

In particular, it emerged from interviews that, as battery-electric and fuel cell vehicle capabilities improve, grids strengthen and diesel regulations tighten, the transport sector is moving from strategic ambition to operational implementation. However, while adoption is accelerating, it remains at an early stage, and for many demand-side actors the challenge is increasingly systemic rather than technological.

Three recurring bottlenecks have been identified. The first relates to infrastructure versus timeframe: hydrogen refueling and electric charging infrastructure deployment, as well as grid upgrades, remain fragmented and slow, relative to corporate decarbonization targets, creating a persistent chicken-and-egg dynamic between fleet procurement and infrastructure investment.

Second, even when the infrastructure is in place, operations often determine the economics. Total cost of ownership parity is highly sensitive to consistent vehicle utilization, with idle assets quickly eroding expected savings. According to logistics actors, a powerful near-term lever for improving utilization is not necessarily new hardware or connectors, but operational orchestration. In practice, this involves coordinating when, where and how trucks charge in order to reduce peak demand, minimize waiting times and lower per-kilometer energy costs. Joint routing and charging optimization has shown the potential to align vehicle flows with station capacity and charger power, directly supporting higher asset productivity.

Orchestration is, however, constrained by the third bottleneck, which is the fragmentation of international frameworks and standards. Regulatory drivers are becoming more sustainability-oriented, yet remain regionally fragmented and mixed in design. For operators running international networks, this misalignment introduces the kind of uncertainty that can affect near-term utilization and revenue planning.

In this context, clear, transparent and predictable licensing practices can help support interoperability, enable cross-border deployment and reduce investment risk, allowing zero-emission technologies to diffuse more rapidly across fleets and regions. Patents remain essential to sustaining innovation in zero-emission trucking, but their contribution to scale depends on how well they align with system deployment and operational realities.

89 WEF (2025c). *Turning Challenge into Opportunity: Supplier Voices from Heavy-Emitting Sectors*. Geneva: World Economic Forum. Available at: https://www.weforum.org/publications/turning-challenge-into-opportunity-supplier-voices-from-heavy-emitting-sectors.

Appendix

A.1 Methodology for patent analysis

Patent identification and mapping to a definition

Transforming a technology definition into a patent data collection is a crucial step when undertaking patent analysis. The most relevant aspect is the method of finding patents that fit the definition. The approach used in this report followed established guidelines, such as those provided by WIPO,[1] to gather the patents to a definition within an optimal relation of precision and recall. More specifically, the approach encompassed extensive searching for keywords and relevant synonyms, scrutinizing patent classes, combining search terms and excluding keywords that were irrelevant to the specific technology we were investigating. This methodical process enabled us to construct a foundation of structured information from the vast patent landscape. It was a crucial step in ensuring that our search was both thorough and targeted.

Data collection and patent counting

- Simple patent families are counted as a proxy for individual inventions in the report. A simple patent family is a set of patents in various countries that relate to a single invention. The technical content covered is considered to be identical. All patent documents have the same priority date or combination of priority dates. The first publication by a member of a patent family counts as the publication year.
- Most analysis in the report refers to numbers of patent families. Only published patent families have been studied.
- Patent families generally include only patents and not utility models, without assessing their legal status.
- The origin of the inventor (inventor's location or residence) is used as a proxy for the source of innovations. For patents with multiple inventors, we count the different locations listed and count the location for multiple inventors of the same origin once.

Utility models have been excluded from the patent analysis in this report because the regional differences and lower inventive threshold for utility models can affect the accuracy and relevance of the analysis.[2] Utility models are not available in every country or region, therefore their inclusion can create inconsistencies in global studies, such as this report, for which comparability across countries and between regions is essential. The requirements for obtaining a utility model are also less stringent than those for a patent and they often cover incremental improvements rather than significant innovations, so including them can dilute the focus on more substantial technological advancements.

1 WIPO (2015). *Guidelines for Preparing Patent Landscape Reports*. Geneva: World Intellectual Property Organization. Available at: https://www.wipo.int/publications/en/details.jsp?id=3938=.
2 WIPO (n.d.). Utility models. Available at: www.wipo.int/web/patents/topics/utility_models.

A.2 Patent indicators

Patent application

To obtain a patent, an application must be filed at the appropriate intellectual property (IP) office with all the necessary documents and fees. The IP office will conduct an examination to decide whether to grant or reject the application. Patent applications are generally published 18 months after the earliest priority date of the application. Prior to that publication, the application remains confidential.

Patent classification

Patent classification is a system that allows examiners of IP offices or other people to code documents, such as published patent applications, according to the technical features of their content. The International Patent Classification (IPC) is agreed internationally. The European Patent Office (EPO) and United States Patent and Trademark Office (USPTO) launched a joint project to create the Cooperative Patent Classification (CPC) in order to harmonize the patent classifications systems between the two offices.

Patent applicant/owner

Patents are filed by an applicant, which can be an organization or a natural person. Applicants are not inventors, even if sometimes they are similar. The applicant is, in most jurisdictions and in most cases, published with the patent and always remains the applicant. The applicant is not automatically the owner of a patent at a given time, even if that is often the case. Patents can be transferred or sold, or the applicant itself can be sold as a company in a merger or takeover. Therefore, the “owner” of a patent might change over time and is not always published.
For proper analysis, to consolidate incorrect spelling and to include merger and acquisition information in the analysis, the report used the ultimate owner concept in the IFI Claims global patent database. The most probable entity was then named as owner.

Patent family

A patent family is a collection of patent applications covering the same or similar technical content and all sharing one or more priority documents. Families are used to count inventions, rather than several patents corresponding to the same subject matter filed in different jurisdictions. There are several definitions of patent families, including simple and extended patent families, depending on the number of priority documents shared (ranging from one to all priority documents). Patent family members are the individual patents filed in those jurisdictions where a patent applicant is seeking patent protection (e.g., WIPO, EPO) and all publications in relation to these. In the present study, we counted simple patent families (using a representative patent family member for each patent family), unless otherwise specified.

Granted patent

Once examined by the IP office, an application becomes a granted patent or is rejected. If granted, the patent gives its owner a temporary right, for a limited time period (normally 20 years), to prevent unauthorized use of the technology outlined in the patent. The procedure for granting patents varies widely between locations in accordance with national laws and international agreements. Note that in the same patent family, an application can be granted in one location and rejected in another.

Inventor country/location

The origin of the inventor (inventor’s location or residence) is used as a proxy for the source of innovation. For patents with multiple inventors, we counted the different locations listed and counted the location for multiple inventors of the same origin once. If no inventor address was available, the patent priority country/location was used as a proxy for the source of innovation.

Priority country/location

The priority country/location is the first location in which a particular invention has a patent application filed, also known as the office of first filing.

Filing country/location

The filing country/location is the legal jurisdiction in which a member of a patent family filed a patent application to seek patent protection.

PCT (WO patent)

The Patent Cooperation Treaty (PCT) is an international patent law treaty concluded in 1970, administered by the World Intellectual Property Organization (WIPO), between more than 140 Paris Convention locations. The PCT makes it possible to seek patent protection for an invention simultaneously in each of a large number of locations by filing a single "international" patent application instead of filing several separate national or regional patent applications. The granting of patents remains under the control of the national or regional patent offices, a stagere ferred to as the "national phase."

European patent (EP patent)

A European patent can be obtained for all the European Patent Convention (EPC) locations by filing a single application at the EPO. European patents granted by the EPO have the same legal rights and are subject to the same conditions as national patents (granted by a national patent office). A granted European patent is a "bundle" of national patents that must be validated at the national patent office to be effective in member locations. The validation process could include submission of a translation of the specification, payment of fees and other formalities at the national patent office. Once a European patent is granted, competence is transferred to the national patent offices. Other regional patents or procedures also exist: the Eurasian patent (EA), African Regional Intellectual Property Organization (ARIPO) patent (AP) for English-speaking Africa and African Intellectual Property Organization (OAPI) patent (OA) for French-speaking Africa.

International patent family

An international patent family is defined as a patent family that has been filed and published in two or more jurisdictions (sometimes also known as foreign-oriented patent families or extended patent families). This contrasts with a domestic-only patent family or a non-international patent family, which consists of a patent family filed in only a single jurisdiction (often known as a "singleton").

WIPO Patent Momentum Indicator

The WIPO Patent Momentum Indicator (PMI) is a data-driven metric that captures the pace and intensity of innovation in global patenting, helping to identify fast-evolving technologies across industries. Developed to highlight technology areas of interest by analyzing both the volume and the growth rate of patenting activities, PMI offers insights into the momentum of patenting activity, making it a valuable metric for stakeholders interested in tracking technological advancements.

Calculation steps:

1. Patent activity level
   - Calculate the average annual number of patent families for each technology trend–modality combination from 2018 to 2023.
   - Normalize these values using a Z-score.

2. Patent activity dynamics
   - Determine the compound annual growth rate (CAGR) of patent families for each combination over the same period.
   - Normalize the growth rates using a Z-score.

3. Total patent momentum score
   - Combine the normalized scores from the activity level and dynamics to obtain a total score for each trend–modality combination.

Relative Specialization Index

The Relative Specialization Index (RSI) compares the published patenting activity in two or more locations within the same technology area. RSI is a measure of a location's share of patent families in a particular field of technology as a fraction of that location's share of patent families in all fields of technology. It accounts for the fact that some locations file more patent applications than others in all fields of technology.

In other words, RSI has the advantage of providing a comparison of two locations' patenting activity in a technology relative to those locations' overall patenting activity. The effect of this is to highlight locations that have a greater specialism in the technology area studied than would be expected from their overall level of patenting, and which might otherwise appear further down the top inventor location lists, and often go unnoticed. A positive RSI value indicates that a location has a higher specialization in a specific field than would be expected, while a negative value indicates a lower specialization than expected for that location.

The RSI is calculated as follows:

$$RSI = \frac{X-1}{X+1}$$

where X is given by,

$$X_{c,t} = \frac{\frac{n_{c,t}}{N_c}}{\frac{N_t}{N}}$$

and

$n_{c,t}$ is the number of published patent families in country c for technology t,

$N_c = \sum_t n_{c,t}$ is the number of published patent families in country c in all technologies,

$N_t = \sum_c n_{c,t}$ is the number of published patent families in technology t in all countries, and

$N = \sum_c \sum_t n_{c,t}$ is the number of published patent families in all technologies and all countries.

A.3 Patent searches

Full details of the patent search strategies used to define the technology areas analyzed in this report can be accessed and downloaded from the WIPO website.[3]

3 See WIPO Patent Landscape Reports. Available at: https://www.wipo.int/en/web/patent-analytics/index#technology.

Heavy-duty road transport – trucks and buses – plays a vital role in the global economy but is also a major source of greenhouse gas emissions. With the vast majority of vehicles still powered by fossil fuels, decarbonizing this sector is essential to achieving climate and energy transition goals. Rapid technological advances are reshaping how goods and passengers are transported, with new solutions emerging across vehicle powertrains, energy infrastructure and digital systems.

The WIPO Patent Landscape Report on Decarbonizing Heavy-Duty Road Transport examines global patent trends in the technologies enabling this transition. It provides a comprehensive and up-to-date overview of innovation across four key areas: low-emission energy sources, energy infrastructure, vehicle efficiency and green digitalization. By analyzing patent activity worldwide, the report offers insights into the technological pathways, leading innovators and geographic patterns shaping the future of low-emission trucks and buses.

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