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Ecological aspects of DC-DC converters in hybrid electric vehicles – a review

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Abstract. This paper aims to conduct a literature review on the ecological aspects of energy DC-DC converters in hybrid vehicles. Modern technologies that enhance energy efficiency and reduce harmful emissions associated with these components are analyzed. The main trends, challenges, and future prospects for developing environmentally sustainable solutions in energy conversion for hybrid cars are presented. Furthermore, the present work emphasizes the necessity of studying and integrating DC-DC converters into engineering curricula to foster innovation and sustainable development in the automotive industry.

Key words: energy efficiency, environmental sustainability, green technology.

Introduction

Vehicles are a major source of greenhouse gases and fine particulate matter, which contribute to global warming. This harms human health, so scientists are trying to reduce the negative impacts of driving traditional internal combustion engines (ICE) on the climate and people. Hybrid electric vehicles (HEVs) and all-electric vehicles (EVs) are rapidly emerging as alternative powertrains for green transportation.

Hybrid cars are an intermediate link between internal combustion engines and electric cars and offer a more environmentally friendly and economical solution in automotive engineering. This is a significant advance in the automotive industry, providing an innovative solution to reduce environmental impact without compromising on the performance of the car. Hybrid cars combine the familiar gasoline engine with an electric one. This helps to lower fuel consumption and reduce harmful emissions into the atmosphere.

In HEVs, electricity is used as the main source of energy for short distances or at lower speeds. At higher speeds when additional power is needed, the gasoline engine is activated, providing the necessary force to move the vehicle. An advantage of hybrid cars is their ability to regenerate energy. Their battery is charged every time it slow down or stop, thus increasing the efficiency and autonomy of the car.

Hybrid vehicles represent an attractive choice for modern consumers. According to sales statistics for new cars classified by power source, provided by the European Automobile Manufacturers Association (ACEA, 2025), it is evident that by 2024, hybrid electric vehicles have solidified their position in second place, accounting for a market share of 30.9% (Fig. 1). Meanwhile, battery electric vehicles remain the third most popular choice among consumers in 2024. Recent data from the ACEA show also that Bulgaria is a leader in the growth of new hybrid vehicle sales within the European Union (EU), both for April and for the first four months of the year. Hybrid vehicles have become the most popular powertrain in the regional market in the last months of 2024, surpassing gasoline-powered vehicles and highlighting European drive toward electrification in automobiles.

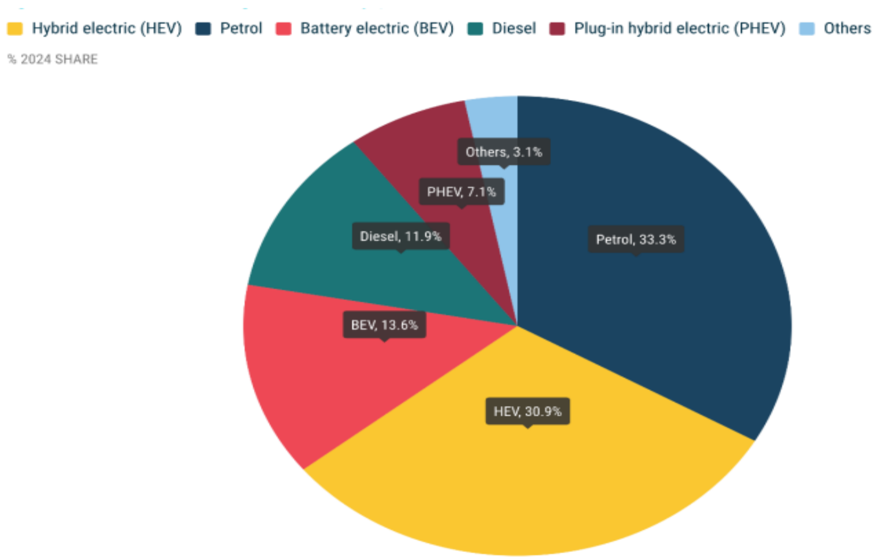

Fig. 1. New EU cars registrations by power source (ACEA, 2025).

Hybrid vehicles are designed to enhance energy efficiency and reduce the harmful impact on the environment. One of the critical components that enables effective management of electrical energy in hybrid systems is the DC-DC converter. Its role is often overlooked, but it is of significant importance both for the system's operation and its environmental efficiency.

Role of the DC-DC converter in hybrid vehicles

HEVs and EVs have multiple architectural configurations. Fig. 2 shows a simplified block diagram of a couple of architectures (Hawes, 2018). For the strong (or parallel) hybrid and the pure EV (no engine), a high voltage (HV) board net is supplied by a large battery, which powers the electric powertrain. Power levels of the inverter and motor/generator range from 50 kW up to and over 180 kW. Along with the large Li-Ion battery, a significant investment is required to develop these architectures. Most of the components support bidirectional power flow. When power flows from the battery to the inverter/motor, the vehicle is propelled. When decelerating, the momentum of the vehicle turns the generator, driving power back through the inverter and charges the battery (regenerative braking). Because of the power levels and heat dissipated, most power converters are water cooled, adding to the cost of the vehicle.

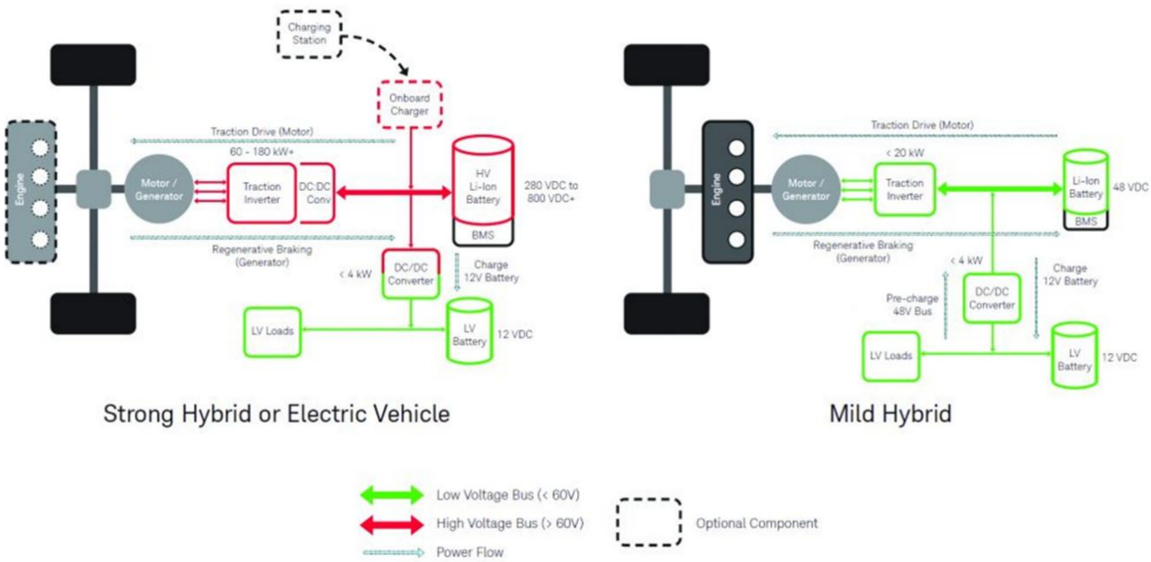

Fig. 2. HEV/EV power train architectures (Hawes, 2018).

In the Mild Hybrid (MH), the motor/generator, inverter, DC-DC converter and battery are all bidirectional. The inverter/motor is not large enough to drive the vehicle by itself (as in the HEV or EV), but instead is used to supplement the engine power during acceleration and recharge the battery during deceleration. This technology also uses a 48 V board net to reduce safety concerns and cost.

The DC-DC converter transforms the direct current (DC) voltage between different components in the vehicle's electrical system, such as: lowering the high voltage from the battery (e.g., 200–400 V) to 12 V to power the onboard electronics (lights, radio, controllers, etc.); enabling bidirectional energy transfer (in plug-in hybrids or energy storage systems) and improving energy efficiency by minimizing conversion losses.

Environmental aspects

The positive environmental aspects of using DC-DC converters include increased energy efficiency, reduced harmful emissions, improved regenerative braking, and the promotion of the electrification of automotive transport.

Increasing energy efficiency

Hybrid Electric Vehicles combine internal combustion engines with electric drivetrains. Their energy efficiency depends on the effective management of electrical energy flow between the battery, electric motor, and onboard electronics. DC-DC converters play a crucial role in this process by transforming voltages between various subsystems with minimal losses. This leads to reduced fuel consumption and consequently lower CO_2 emissions. The main performance indicators for the energy efficiency of converters are:

- Conversion efficiency coefficient (%): Typically, its value ranges from 90% to 98%;
- Thermal losses: Minimizing heat is key to sustainable operation; the smaller the losses, the lower the cooling requirements.

Engineering trends indicate that DC-DC converters are increasingly combining functions such as buck, boost, and bidirectional conversion with modern controllers (e.g., PI, any combination of PID, fuzzy logic controllers) to achieve high efficiency and improvements in braking recovery (Evuri et al., 2017).

Buck (Step-down) Converter. The buck converter is used to convert high voltage to low voltage. It is characterized by extremely high efficiency (greater than 95%). Its advantages include a simple topology, compact and reliable design, and reduced thermal losses. It is used to power a 12 V onboard system from an HV battery (e.g., 400 V) and to support auxiliary electronic modules (lighting, control systems, air conditioning).

Boost (Step-up) Converter. The boost converter is used to increase low input voltage to a higher stabilized output voltage. It uses the same core components as buck converters but in a different configuration. Its efficiency is approximately 90%. The advantages of a boost converter include enabling HV battery charging from a 12 V source during regenerative braking and assisting in starting when the battery is partially discharged. It is used for charging high-voltage components from low-voltage sources and maintaining stability in low-voltage conditions. The Interleaved DC-DC Boost Converter for Hybrid Electric Vehicles, proposed by Ahmad et al. (2021), offers several advantages over conventional boost converters, including: reduced switching losses, higher output voltage at lower frequencies, reduced electromagnetic interference, and better thermal resistance.

Buck-Boost Converter. The buck-boost converter is a versatile DC-DC converter that can either step down or step up voltage according to specific needs. It provides flexibility in unstable power supply environments. Its typical efficiency is 88%, but a well-designed buck-boost converter can achieve efficiencies above 90% (Cale, 2024). It is essential to provide protection against voltage surges and current spikes. These converters allow adaptive operation of EV/HEV under variable conditions, enhance regenerative braking by converting energy back to the HV battery, support auxiliary systems (lighting, control) even under unstable power, and extend the life of batteries and electronic components by controlling currents and ripples.

Bidirectional Converter. A bidirectional converter allows energy to flow in both directions, which is particularly important during regenerative braking (Govardhan et al., 2022). Its efficiency is approximately 92%, leading to less energy dissipation (Liu et al., 2023). It provides better utilization of recovered energy (during EV braking), requires less cooling, which results in lower energy consumption. Bidirectional DC-DC converters enable both charging and discharging of batteries with the same power module, improving the system's compactness, response during transient processes, overall efficiency, and reliability. Although challenges remain in manufacturing these converters, the environmental and energy benefits of using bidirectional DC-DC converters are undeniable (Zhan, 2018). During regenerative braking, energy is restored to the battery; they ensure a longer battery life because CC/CV management prevents overcharging and deep discharge; they result in less loss and heat due to synchronous rectification and optimal management. The reduction in the need for additional hardware leads to fewer components, and thus a lower carbon footprint in production.

Multiphase Converter. The multiphase converter uses several parallel circuits for better current distribution. Its efficiency is approximately 96%. It provides lower losses, less heating, and improved cooling. Renken (2010) demonstrates a multiphase architecture to reduce current ripple and thermal losses.

The graph in Fig. 3 summarizes the energy efficiency data of various types of DC-DC converters used in hybrid and electric vehicles.

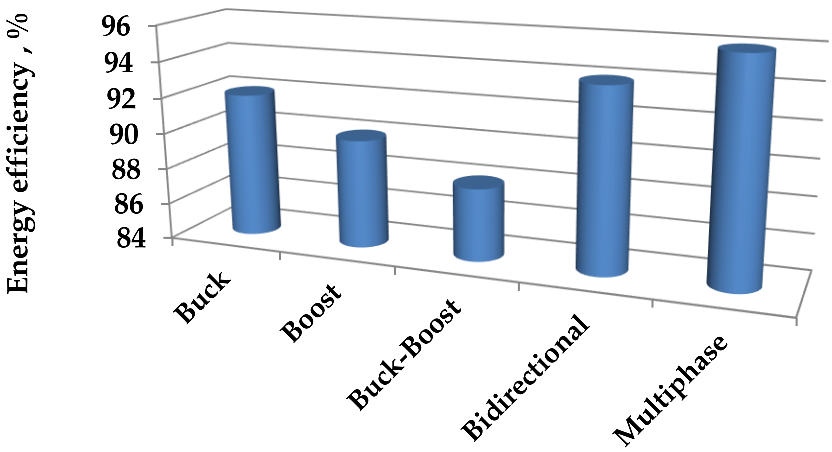

Fig. 3. Energy efficiency of different DC-DC converters.

With the growing demand for energy-efficient, compact, and high-frequency electronic systems, silicon devices are reaching their physical limits. Therefore, scientific research focused on the application and evaluation of new materials in DC–DC converters is not only relevant but also essential to support sustainable development and the energy transformation of modern society (Waradzyn et al., 2020; Kaur, 2025). The use of new materials in the production of DC-DC converters also leads to an increase in energy efficiency. Such materials include wide-bandgap semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC). Research shows that devices based on Gallium Nitride (GaN) and Silicon Carbide (SiC) exhibit significantly higher efficiency and smaller sizes compared to silicon transistors (Udabe et al., 2023). High-frequency switching (100–500 kHz) reduces the need for large inductive and capacitive elements.

In Kruse et al. (2017), a prototype is examined with an efficiency of 94.4% at a frequency of 10 MHz and a density of 6.25 W/cm^3. The article outlines the advantages of using GaN in bidirectional converters. In Hawes (2018), it is emphasized that the use of wide-bandgap semiconductor components (Wide Bandgap – SiC and GaN) leads to a reduction in switching losses. The converter in question operates at higher frequencies, allowing the use of smaller magnetic components. There is a lower need for cooling and a reduced internal power consumption by the converter. As a result, a higher overall energy efficiency of the powertrain and lower fuel consumption (in HEV) or electricity consumption (in EV) is achieved under real-world conditions.

The article of Kaur (2025) compares the efficiency of buck converters with MOSFET and GaN-FET, with those based on GaN achieving higher efficiency and enabling higher operating frequencies. In the work of Ortíz-Marín et al. (2023), transformers in a high-efficiency isolated DC-DC converter are studied, with an efficiency of up to 97%. In Waradzyn et al. (2020), a new architecture for a resonant converter with switchable capacitors (Switched Capacitor Voltage Doubler – SCVD), based on GaN transistors, is examined. The experimental results presented show a maximum efficiency of 99.228%. It should not be overlooked that for voltages above 650 V, SiC remains the preferred option, especially for bidirectional converters with high voltage (e.g., 0.5–2 kV).

The use of such new materials not only improves the overall efficiency of converters (reaching up to 96–98%) but also reduces their size, weight, and need for active cooling—critical factors in mobile and high-performance applications like electric vehicles. From 2023 to 2025, the trend is toward multi-port solutions that integrate battery power, ultra capacitors, and charging stations, improving management and reducing losses. The use of wide-bandgap semiconductors (SiC, GaN) further increases the efficiency and reduces the size of the devices.

Contemporary research from 2023 to 2025 clearly shows a shift towards multiport DC–DC converter architectures that integrate battery, ultra capacitor, and charging-station ports, enhancing control flexibility and lowering losses (Farajdadian et al., 2024). Simultaneously, the adoption of wide bandgap semiconductors (SiC, GaN) has been proven to boost conversion efficiency and reduce device size, thanks to higher switching speeds and lower conduction losses (Gevorkov et al., 2023).

Table 1 presents a comparison of the efficiencies, operating frequencies, and applications of different types of DC-DC converters used in hybrid and electric vehicles. Modern DC-DC converters have high efficiency (up to 95–98%), significantly reducing energy losses during conversion. The increased efficiency leads to lower fuel consumption and reduced carbon dioxide emissions, particularly in urban environment (Kanevski et al., 2024; Kanevski et al., 2025).

Table 1. Comparison of some parameters and applications of different types of DC-DC converters used in hybrid and electric vehicles.

No.	Type of the converter	Efficiency	Operating frequency, kHz	Application
1.	Conventional Buck	88	100	Basic 12 V on-board network
2.	Synchronous Buck	94	200	Improved 12 V system
3.	Buck-Boost	91	150	Flexible AC voltage conversion
4.	Bidirectional	92	200	Bidirectional charging and regeneration
5.	GAN based	96	500	High-efficiency HEV/EV systems
6.	SiC based	95	400	High temperature conditions in EV

Reducing emissions through DC-DC converters

DC-DC converters have a key role in hybrid electric vehicles not only for optimizing power distribution, but also as a direct factor in reducing harmful emissions.

The study of Kumar & Gaur (2012) outlines six HEV operating modes, including: Pure electric drive for low power demand, resulting in zero emissions in urban traffic; Hybrid mode for higher demand where the DC-DC converter manages the energy flow between the battery, inverter and electric motor, providing the right voltage and current. The benefits are optimized fuel and power sharing. The third mode is Regenerative braking, in which the battery is charged and kinetic energy is utilized. These modes, regulated via the DC-DC converter, enable dynamic energy redirection, leading to reduced fuel consumption and lower CO_2, NO_x, and HC emissions

In the study of Evangelou & Rehman-Shaikh (2017), the fuel economy of series HEVs is shown to improve by dynamic variation of the voltage of the DC-link that joins the powertrain converters.

Although Hawes (2018) does not present quantitative empirical data directly demonstrating a reduction in carbon emissions, he builds a clear technical and logical connection between DC-DC converter design and the environmental sustainability improvements in hybrid and electric vehicles.

Nguyen et al. (2022) developed a multiport bidirectional DC-DC converter that integrates a battery, ultra capacitor, and fuel cell (FCV/HEV). This innovative architecture enables efficient power conversion, reduced switching losses, and effective flow control, which lowers overall energy losses.

All of this leads to improved system efficiency, optimal fuel utilization, and a tangible reduction in harmful emissions.

Improved Regenerative Braking

Regenerative braking is one of the primary mechanisms through which hybrid electric vehicles enhance their energy efficiency. This technology allows the vehicle to recover kinetic energy during braking and convert it into electrical energy. The recovered energy is stored in the battery and can be used later to power the electric motor.

In hybrid vehicles, regenerative braking is often combined with an internal combustion engine (ICE), enabling maximum utilization of the energy recovery capability. During braking or deceleration, the electric motor functions as a generator, converting kinetic energy into electrical energy.

DC-DC converters support the regenerative braking process by providing the necessary voltage conversion between the vehicle's batteries and energy systems. When the vehicle enters regenerative braking mode, the battery voltage can fluctuate depending on the current state of charge and other factors.

In this context, DC-DC converters help ensure a stable and optimized energy flow, as they can increase or decrease the voltage for effective battery charging, regardless of changes in the system's energy conditions. This is crucial for hybrid vehicles that combine both a battery and an internal combustion engine, as they must manage various energy sources under different driving conditions. This reduces the need for additional charging and fuel consumption. Better charge/discharge management with the help of DC-DC converters improves the regeneration efficiency by up to 30%.

In Xie et al. (2023), a theoretical description, mathematical model, and simulation results are provided, which convincingly demonstrate the regenerative braking capability of the integrated DC/DC converter with a non-isolated multi-port scheme that integrates a unidirectional port for the fuel cell and a bidirectional port for the battery and load.

Tong et al. (2025) provide a comprehensive review of bidirectional DC-DC converter topologies used in hybrid energy storage systems (HESS). The authors emphasize that regenerative braking depends not only on the converter itself but also on the structure of the HESS, which must combine high energy density (battery) with high power capability and fast dynamics (supercapacitor). To achieve this, converters are required that can rapidly absorb the recovered energy, minimize switching losses, and ensure bidirectional current flow between the sources and the DC bus.

In their review, Jui et al. (2024) present an in-depth analysis of modern energy management approaches in hybrid electric vehicles using machine learning (ML). One of the key focuses of the paper is the role of regenerative braking (RS) as an opportunity for energy recovery and consumption optimization. A central component that enables the implementation of these strategies is the DC-DC converter. It acts as an interface between the different components of the hybrid energy storage system (HESS) and the main power bus. The article highlights that DC-DC converters provide bidirectional energy flow, which is essential for receiving and distributing the energy generated during braking. Moreover, their efficiency and dynamic response are critical for how effectively an EMS strategy can react to RS events.

The work of Sayed (2019) emphasizes the important role of regenerative braking in recovering energy during vehicle deceleration. Instead of using a standard alternator to charge the 12 V battery, the system extracts energy from the high-voltage (HV) battery, which is charged during regenerative braking. This allows for the complete utilization of the recovered energy, improving braking comfort and increasing the overall efficiency of the vehicle. The DC-DC converter discussed in the article provides isolation through a high-frequency transformer, uses a three-stage architecture with smooth switching, and supports bidirectional energy transfer. This is particularly important for integration with regenerative braking, as it allows energy from the main HV battery (200 V NiMH) to be safely transferred to the 12 V LV battery. The applied ZVS (zero-voltage switching) topology significantly reduces switching losses in the power transistors by using the inductances of the transformer and floating capacitors to achieve soft turn-on/turn-off of the semiconductor elements. The author demonstrates that the efficiency of the converter reaches up to 90%, even at a frequency of 40 kHz. The applicability of the circuit is demonstrated through a real example with a Toyota Prius vehicle, which uses a 200 V NiMH HV battery for propulsion. The proposed converter circuit is designed to replace the alternator, leading to fewer mechanical losses and improved fuel efficiency.

Honda also uses similar technologies that combine regenerative braking with DC-DC converters for efficient energy management and recovery of electrical energy during braking. The Honda Two-Motor Hybrid-Electric Powertrain system is the result of more than a decade of development and optimization of hybrid technologies, combining high fuel efficiency, low emissions and dynamic behavior (Honda, 2024). This platform has been successfully implemented in models such as the Honda Accord, CR-V and Civic, and is distinguished by the intelligent integration of electrical and mechanical components to achieve maximum energy efficiency, including through regenerative braking. At the heart of the system's energy architecture is a DC-DC converter integrated into the Power Control Unit (PCU). It performs several critical functions: it converts high-voltage electrical energy from the hybrid battery (typically around 200 V) to the low-voltage systems (12 V) required for standard vehicle electronics; it works in sync with the Intelligent Power Unit (IPU), which manages the battery's state of charge and coordinates the flow of energy during regenerative braking and internal combustion engine charging. Over the generations of the system, the size and weight of the PCU and the integrated DC-DC converter have been significantly reduced (up to 27% lighter and 23% more compact), while increasing efficiency and the ability to be integrated into various models.

Promoting the Electrification of Transport

According to a study by the International Energy Agency (IEA, 2021), the transport sector is responsible for approximately 24% of global CO_2 emissions, and the electrification of transport can significantly reduce this share. Electrification of transport not only reduces dependence on external fuel sources but also lowers CO_2 emissions and other harmful substances such as NO_x and CO. The transition to electric vehicles could reduce global emissions from transport by 50% by 2050 (IEA, 2021). Electrification of transport involves the shift from traditional internal combustion engines to electric drive systems, which can be powered by batteries, fuel cells, or hybrid technologies. The transition to electric vehicles is crucial for reducing carbon emissions, which are a primary cause of global warming and air pollution. The widespread use of DC-DC converters facilitates the integration of more complex electrical systems, which is a step toward full electrification and the shift to cleaner vehicles.

DC-DC converters play an important role in hybrid vehicles, providing efficient management of the energy flow between various power sources. Hybrid cars combine an internal combustion engine (ICE) and an electric motor powered by a battery, allowing for more efficient use of energy and reduced fuel consumption.

As previously noted, DC-DC converters are used to convert the energy from the high-voltage batteries of the vehicle into a lower voltage required to power various electrical systems and accessories of the vehicle. It has been shown that in hybrid vehicles, these converters not only ensure a stable energy flow between the batteries and the electrical system but also play a key role in the regenerative braking process.

During braking or deceleration, the regenerative braking system uses the electric motor as a generator, converting kinetic energy into electrical energy. This energy is stored in the batteries and can be used to power the vehicle's electrical system. DC-DC converters optimize this process by ensuring the proper conversion of energy, which reduces losses and increases system efficiency.

Weaknesses of Using DC-DC Converters in Hybrid Vehicles

From the above, it follows that DC-DC converters play a central role in hybrid vehicles by providing efficient management of energy flow between various power sources, such as batteries and electrical systems. They are necessary for voltage conversion, thus optimizing battery charging and the operation of various vehicle components. Despite their importance, the use of DC-DC converters has some drawbacks and limitations. Some of the main challenges include the use of rare and toxic materials, leading to environmental risks, as well as the generation of electronic waste that requires effective recycling and management methods. Additionally, the efficiency of these devices can be highly dependent on climatic conditions, as extreme temperatures may lead to reduced performance. Despite advances in technology, these weaknesses highlight the need for a better understanding and improvement of DC-DC converters in the context of the sustainable future of transport.

Use of Rare and Toxic Materials

DC-DC converters in hybrid vehicles contain components that require rare and potentially toxic materials. For example, the semiconductor devices used often include metals such as gallium, arsenic, and germanium, which are difficult to extract and may have a negative environmental impact if waste management is inadequate.

In the study by Chakraborty et al. (2019), various aspects of the use of DC-DC converters in hybrid and electric vehicles (EVs and HEVs) are discussed, with the authors focusing on the topologies of the converters and their energy efficiency. While the primary focus is on electrical efficiency and improvements in the design of these components, important conclusions can be drawn about the environmental and energy risks associated with them. The technology described for DC-DC converters requires the use of various semiconductor materials. Metals that are sometimes extracted from rare minerals are used in all components. These materials are valuable but also difficult to extract. Furthermore, the extraction of these chemical elements can lead to environmental issues, including water and soil pollution, as well as difficulties in recycling their waste.

Generation of Electronic Waste

With the increasing deployment of hybrid and electric vehicles, the amount of generated electronic waste is also increasing. DC-DC converters, as part of the vehicle's electronic systems, contribute to this waste.

Electronic waste (e-waste) is one of the fastest-growing streams of solid waste globally. Less than a quarter of the electronic waste produced worldwide in 2022 was officially recycled (WHO, 2024); however, e-waste streams contain valuable and limited resources that can be reused if recycled appropriately. Therefore, e-waste has become an important source of income for individuals and some communities. People living in low- and middle-income countries (LMICs), especially children, face the most significant risks from e-waste due to a lack of proper regulations and enforcement, recycling infrastructure, and education. Despite international regulations aimed at controlling the transportation of e-waste from one country to another, its cross-border movement to LMICs continues, often illegally. E-waste is considered hazardous waste as it contains toxic materials and can produce toxic chemicals when improperly recycled. Poor recycling of e-waste is a public health and safety threat.

Electronic devices contain many different toxic substances. Consumers are unlikely to come into contact with these substances while the devices are functional. However, when they become waste, these toxic substances can be released into the environment if the devices are managed through environmentally harmful practices and activities. Many unhealthy practices have been observed at e-waste sites, including: dumping in landfills, on land or in water bodies; deposition alongside regular waste; opening, burning, or heating, etc. Improper recycling and disposal of these components can lead to soil and water pollution with heavy metals such as lead and cadmium, which are harmful to human health and ecosystems.

One way to reduce the harmful impact of e-waste is through effective recycling of the components of DC-DC converters. Proper waste management can reduce the amount of toxic substances that enter the environment. This requires innovations in the recycling of electronic components, as well as improved infrastructure for collecting and processing e-waste.

Reduced Efficiency under Extreme Climatic Conditions

Despite advances in DC-DC converter technology, they are sensitive to extreme climatic conditions, which can affect their efficiency and reliability. The impact of high and low temperatures on the performance of DC-DC converters is crucial to ensure stable and efficient operation of vehicles, especially in different geographical and climatic conditions. Temperature is one of the key factors limiting the performance, lifespan, and stability of DC-DC converters, particularly when used in high-temperature environments (e.g., automotive electronics).

High temperatures can lead to overheating of components, reducing their efficiency and potentially causing damage. In Wang et al. (2016), it is shown that temperature has a direct and significant impact on the electrical, mechanical, and durability characteristics of DC-DC converters. Temperature changes the characteristics of the semiconductors used, as well as the passive elements (inductors and capacitors). The importance of cooling is emphasized as critical when designing converters for high temperatures. Without adequate cooling, thermal buildup can lead to thermal breakdown, component failure, and converter failure. Therefore, optimal material selection, cooling, and intelligent management are essential for operation across a wide temperature range.

Temperature affects the performance of lithium-ion batteries used in HEV systems (Mousaei, 2023). High temperatures lead to accelerated aging, while low temperatures lead to capacity and efficiency loss, which directly impacts the DC-DC converters powered by these batteries, leading to reduced performance of the DC-DC converters and decreased energy efficiency of the vehicle.

Based on the review, a SWOT analysis was performed to assess the environmental aspects of using DC-DC converters in hybrid vehicles (Fig. 4).

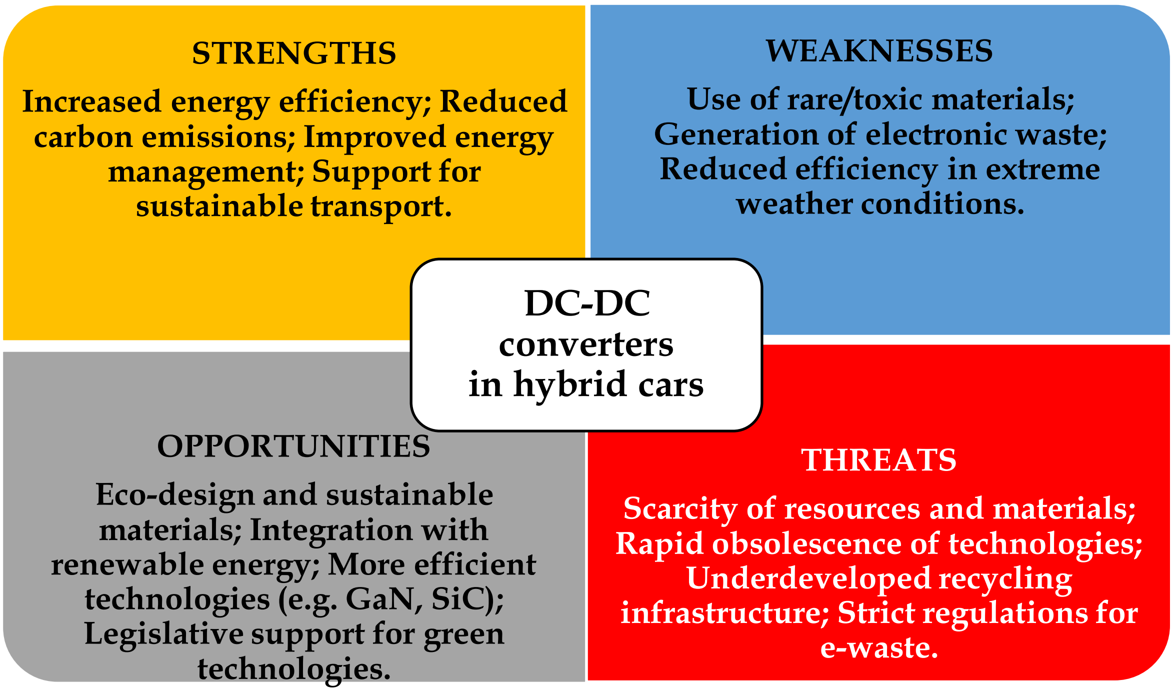

Fig. 4. SWOT analysis of the environmental aspects of the use of DC-DC converters in hybrid vehicles.

DC-DC converters have an important role in the environmental efficiency of hybrid vehicles by improving energy efficiency and reducing carbon emissions. However, the production and disposal of these devices create environmental challenges. Careful resource management and innovations in recycling and sustainable manufacturing of DC-DC converters are required.

DC-DC Converters for Hybrid Vehicles in Engineering Education

The SWOT analysis shows that DC-DC converters have a key role in reducing energy losses and lowering carbon emissions. On the other hand, they are associated with the need to explore and introduce new technologies for their production to enhance their efficiency and manage natural resources. Engineering students, particularly those in the "Automotive Electronic Systems" or related fields, are trained to design, optimize, and maintain these complex systems. Technological advancements support this process, as students may create models of the converters they design in various simulation environments and investigate how the efficiency coefficient and other parameters change depending on the topology, materials used, or environmental factors (Uzunov et al., 2015). In this context, the education should cover theoretical knowledge, practical skills, and innovations that are essential for modern hybrid vehicle engineering. Education in this field will help future engineers understand the importance of sustainable technologies and how to design devices and systems that minimize environmental impact.

Conclusions

Summarizing the review of existing literature, it can be concluded that the development of environmentally oriented DC-DC converters is crucial for improving overall energy efficiency and reducing the environmental impact of hybrid electric vehicles. Despite the progress achieved, several challenges remain, such as material optimization and minimizing energy losses, which need to be addressed in future research. Additionally, incorporating the study of DC-DC converters into engineering education is essential to prepare future engineers capable of advancing sustainable energy solutions. This comprehensive approach will contribute to the more sustainable development of the automotive industry and better environmental preservation.

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