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Review

Renewability and Robustness Analysis and Review for Sustainable-Technology Propulsion Systems in Modern Transportation Infrastructure Administration

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Featured Application: Sustainable and reliable distance energy transfer prototypes.

Abstract: Recently, major climate events highlighted the increasing need to use sustainable technologies in the transportation domain. Energy production infrastructure, storage, and propulsion systems still rely on non-sustainable technology for economic growth. Therefore, this study reviews the modern transportation propulsion systems and transportation infrastructure components, describing the possible outcomes for several future directions based on prototypes and study advances. The in-production vehicles were reviewed for providing immediate, robust, and renewable solutions for the existing non-sustainable transportation infrastructure. The study continues with extended-capability vehicles and their limitations and vulnerability based on the current infrastructural circumstances. An alternative energy transfer infrastructure has been concluded to possibly provide the necessary capabilities to approach a neutral carbon footprint and mitigate ongoing climate adverse events. The hypothetical prototype uses distance energy transfer to bypass the described environmental constraints and provide a direction for achieving a possibly sustainable and economically evolving infrastructure.

Keywords: energy management systems; electric vehicles; hybrid powertrain; internal combustion engine; magnetic levitation; distance energy transfer; sustainable transportation infrastructure

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1. Introduction

Planetary climate regulation consists of vast and complex ecosystems interconnected to achieve negative feedback in stabilizing the global temperature at life-thriving conditions [1]. Previously, the computational model highlighted the adaptation of living organisms to climate change and the climate regulation change based on living organisms' characteristics. Above a certain global warming threshold, a positive feedback loop effect becomes prominent, rendering the planetary conditions uninhabitable due to the excessive temperature, possibly resulting in mass extinction.

Because the IPCC (Intergovernmental Panel on Climate Change) models repeatedly underappreciated the global temperature increase [1,2], a commitment to zero emissions must be urged. The global temperature increase is highly non-linear in contrast to the expected behaviors [1], emphasizing the need for urgent action to achieve a sustainable transportation infrastructure. This course of action could prevent future extreme weather conditions, as these were related to climate change and are expected to become more frequent [3,4].

Because the IPCC forecasts were under-appreciated, the consequences of global warming are already expected to be worse than the ones described in the 2023 assessment report cycle. For an additional 3 °C above the nominal temperature, these changes describe a maximum increase of 187% in burn areas across Europe, 12 times more frequent heat waves in Southern Africa, and 29% biodiversity loss [5]; however, based on studies, severity is expected to be greater soon [1].

Even with the increase in sustainable technology during recent years, non-renewable means still dominate worldwide energy generation, as illustrated in Figure 1.

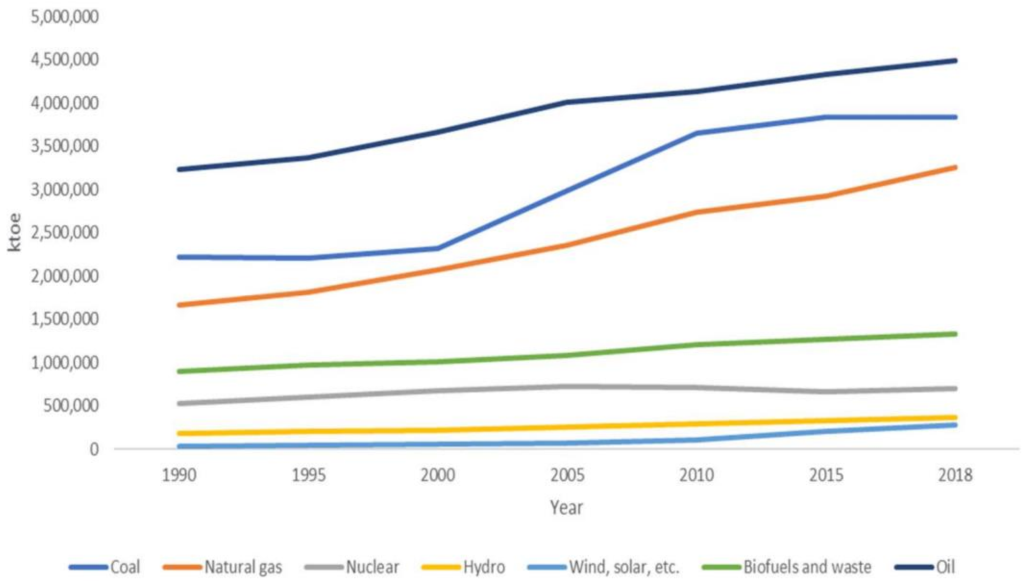

Figure 1. Worldwide energy generation shows a greater gradient for several non-sustainable generation means, for example, oil and natural gas, in contrast to wind and solar energy [6].

From all in-service vehicles, statistics describe the use of fossil fuels in 95% of all propulsion means, highlighting the dependency on non-renewable technologies. Over 200 million tons of oil-equivalent fuel was consumed to operate these machines in 2020 [7,8]. These transportation solutions are currently known for their robustness and extended travel range. However, road vehicles still provide a long-term sustainability issue regarding greenhouse gas emissions due to the limited amount of available fossil resources and other non-sustainable materials [9].

Furthermore, in the European Union, carbon dioxide emissions increased by 21% between 1990 and 2018 [10]. Global statistics describe transportation systems as representing 20% of all greenhouse emissions, of which more than 75% account for road transportation networks [11,12]. Fully electric vehicles were developed as an initiative to replace completely non-renewable propulsion systems. However, due to the lack of high-energy density storage systems and charging stations spread across less developed areas [13,14], the vehicle travel range is reduced compared to ICE (Internal Combustion Engine) vehicles [15].

The current circumstances pose many difficulties in migrating an entire infrastructure to a sustainable solution. This would involve manufacturing, transportation, and all other industries committed to zero emissions [16]. Before gaining acceptance, electric vehicles must undergo several improvements [17], such as weight reduction and energy density improvement. This highlights the difficulty of transitioning from fossil fuels to electrification in modern transportation infrastructure and solutions.

In contrast to existing studies evaluating only urban transportation [18] or economic sector impacts [19], the present analysis demonstrates several limitations of in-service vehicles, followed by future vehicle and infrastructure changes where applicable. The review considers using the actual circumstances to provide an immediate, robust, renewable transportation solution. The proposed hypothetical scenario could provide advantages over these conventional limitations, considering the energy grid's expansion as vulnerable and the presence of operators as part of periodic maintenance, highlighting concerns related to health impacts. As described by researchers, a new power distribution system would be necessary to commit to zero carbon emissions [20]. However, both the occurring consequences and the scale of demand might be underestimated in migrating a non-sustainable transport infrastructure to a robust and renewable solution [19,21].

Therefore, robustness and renewability were studied for each impediment in achieving the improved transportation network committed to a neutral carbon footprint, describing its respective energy propulsion and management systems. The study initially covers ICE-based vehicles, followed by their improvements and sustainability concerns, continuing afterward with electric vehicles. Expanded capability vehicles were also studied, followed by grid vulnerability for railway vehicles and modern equipment's impact on the operator's health. A hypothetical addition for one of these case studies is plausible to provide the desired infrastructural characteristics.

2. Vehicle Topology Advancements

Recent research studies have progressed in developing new battery technologies, allowing electric vehicles to achieve a range and performance comparable to conventional ICE-powered designs. However, as this technology must be optimized, key factors such as price, performance, and autonomy affect the decision to purchase either an electric vehicle emphasizing sustainability or an ICE-powered vehicle, representing a robust solution [22]. Furthermore, charging station distribution over a country's territory also determines this decision [23,24]. Last but not least, as mentioned in [25], most of the charging stations are spread outside of Eastern Europe, with the European Union setting a goal for increasing the charging point number [26], as shown below in Figure 2.

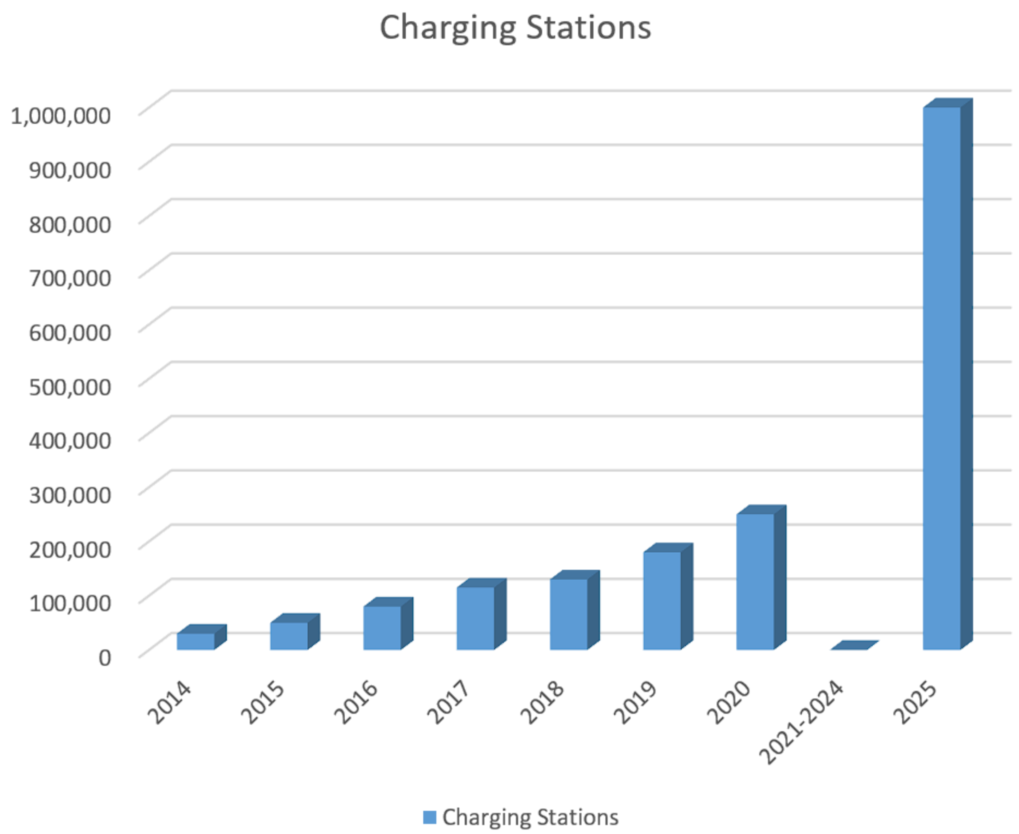

Figure 2. Green Deal charging stations target.

Most internal combustion engines store the propulsion-providing compound as a refined petroleum product or fossil fuel. At the same time, the battery pack represents the usual energy storage system for electric vehicles for which the electric motor provides mechanical work. Hybrid vehicles use both the ICE and electric motor approaches combined into a modified drivetrain system, for which, however, the main propulsion mechanism is still represented by the combustion engine. Despite further enhancing the overall vehicle performance, such drivetrains are still based on non-renewable technology [27]. Figure 3 covers several block diagrams for currently available drivetrain topologies.

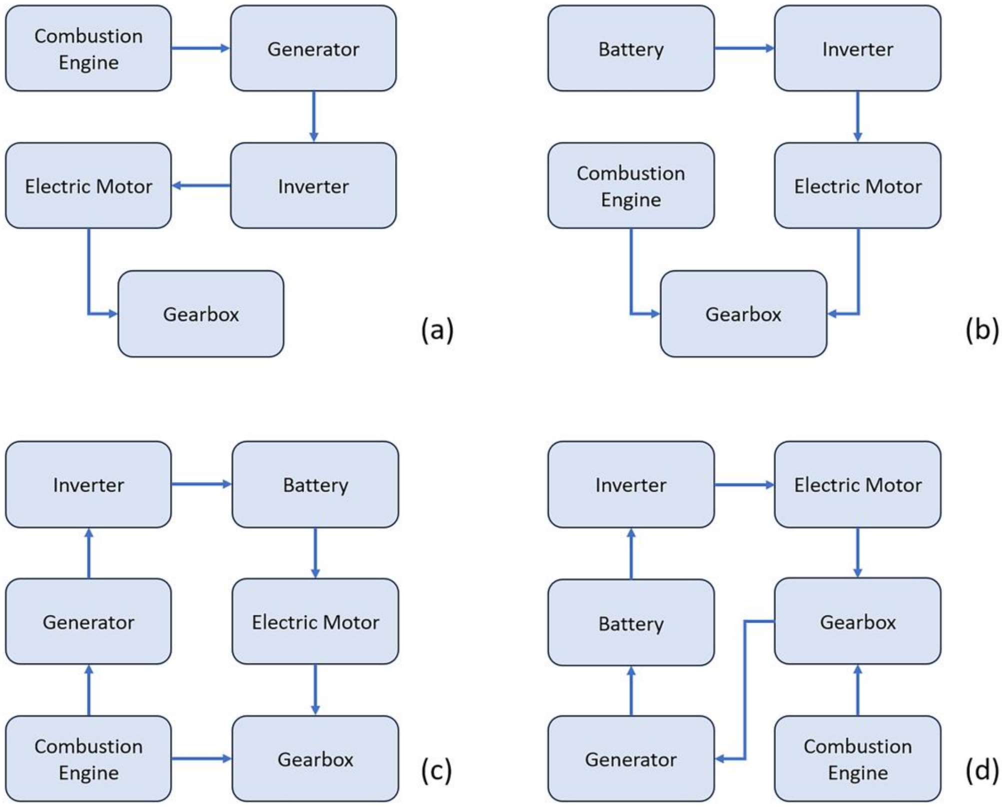

Figure 3. Powertrain designs in HEVs (Hybrid electric vehicles)—(**a**) series hybrid drivetrain, (**b**) parallel, (**c**) series and parallel, and (**d**) power-split.

The mechanical part of such vehicles is still affected by some constraints typical to ICE vehicles. To better understand more complex renewability issues in hybrid electric vehicles, the following sections cover an overview of the latest available improvements and renewability possibilities of ICE technologies. Based on the existing state-of-the-art studies and prototypes, the renewability of these available solutions is considered alongside evaluating long-term robustness, maintenance, and operation costs.

3. Internal Combustion Engine

Before the development of CRDI (Common-Rail Direct Injection) technology, the fuel amount to each cylinder was supplied using mechanical means for all types of internal combustion engines. The previously replaced analog fuel delivery systems, such as in-line injection fuel systems or carburetors, could not continuously control and adjust the quantity of fuel delivered, resulting in improper combustion cycles, increased pollution, and multiple health concerns [28].

The CRDI variant of combustion engines remains present in a broad range of propulsion systems for generic purpose vehicles, such as vehicles in the automotive industry (e.g., passenger cars), cruise or cargo ships, commercial or private aircraft, and others.

3.1. Common-Rail Direct Injection

The CRDI system emerged due to the increased need to accurately control the fuel delivered to each cylinder, independent of camshaft angular velocity, and to increase the overall efficiency and emission compliance of ICEs [29]. A basic schematic for this fuel delivery system is presented below in Figure 4.

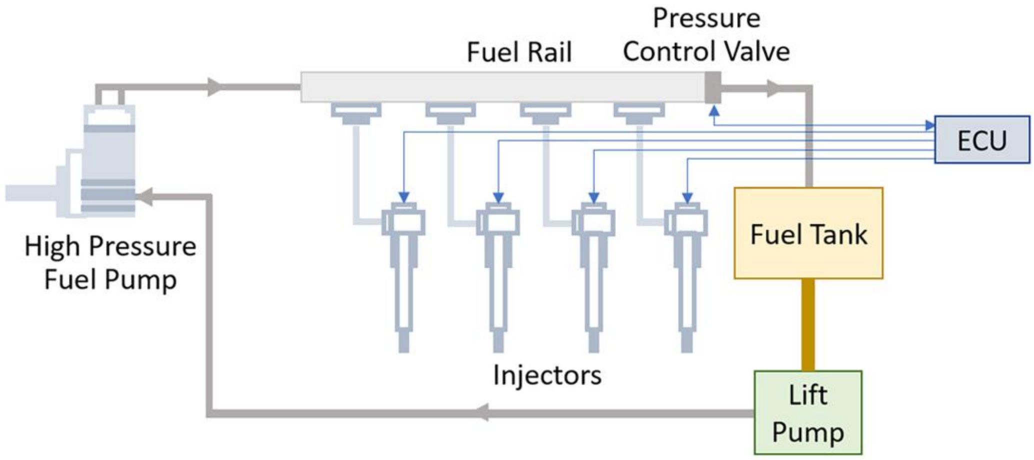

Figure 4. EFI (Electronic Fuel Injection) common-rail system.

This direct injection system supplies all injectors with high-pressure fuel, and the fuel pressure adjustment is partially achieved by electronic parts, increasing to a saturation point as the camshaft speed increases. While the fuel pressure is maintained quasi-constant, the injector opening time controls the amount of fuel delivered into each cylinder, with an additional fuel line returning the excess fuel to avoid a build-up in rail pressure [30].

For either fuel type (gasoline or diesel), common rail systems can be found in many powertrain systems, resulting from meeting the latest global emission standards. Even with the known issues, such systems were further improved to achieve better overall performance.

3.2. CRDI System Improvements

A typical improvement of this propulsion system is the combustion of a small amount of fuel injected into the cylinder before the main combustion injection, also called pilot injection, improving performance and decreasing the operation noise [31]. This process can be further adjusted depending on the piston position in the cylinder [32]. However, as shown below in Figure 5, in contrast to less accurate fuel delivery strategies [33], based on low-pressure fuel pumps, additional catalytic reduction methods must be implemented for direct injection systems to maintain the emissions within the compliance limits.

The stoichiometric operation of the GDi engine shows compliance close to the Euro 6b standard, while the old MPFI topology still shows a better emission performance (Euro 6c) [34], despite decreased fuel efficiency. This happens due to the increased fuel pressure and compression ratio in direct injection topologies, resulting in combustion cycles at elevated temperatures. This, in turn, generates a greater quantity of harmful gas emissions and particulate matter [35]. However, as specified in [36], researchers achieved a better operation regime than conventional GDi engines. According to [37], adjusting pilot and post-injection fuel quantities decreased certain nitric oxide chemical compounds while other harmful compound quantities increased.

To mitigate the emissions further, artificial intelligence could provide a synthesized diagnostic in the event of any component malfunction [38] or as an option to optimize fuel combustion further.

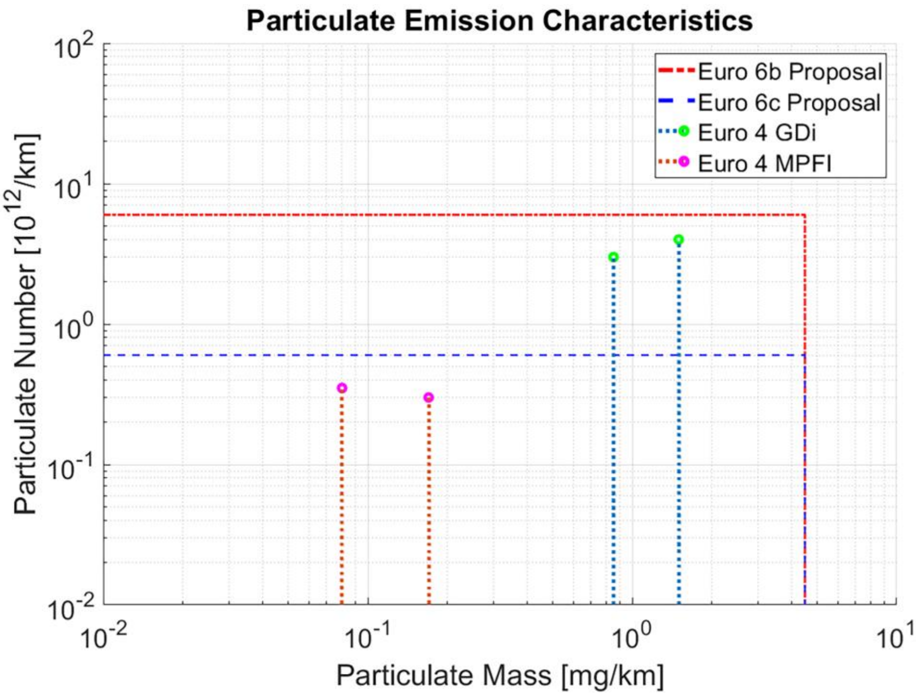

Figure 5. Particulate emission characteristics of an improved CRDI GDi (Gasoline Direct Injection) engine show increased pollution compared to old topologies, such as MPFI (Multi-Point Fuel Injection) indirect injection fuel system.

3.3. Auxiliary Catalytic Systems

SCR (Selective Catalytic Reduction) systems are auxiliary exhaust catalyst systems that decompose harmful compounds from high-temperature combustion cycles [39]. As shown below in Figure 6, the process decomposes engine emissions into non-harmful reaction products.

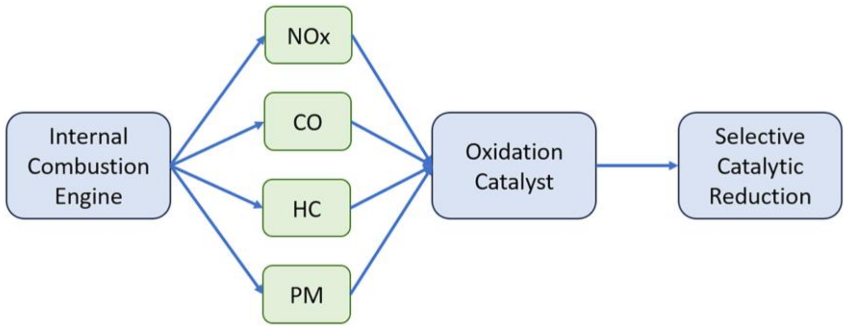

Figure 6. The SCR process. From top to bottom, the engine emissions are nitric oxides, carbon monoxide, hydrocarbons, and particulate matter. The products expected after the SCR catalyst represent nitrogen, carbon dioxide, water, and particulate matter.

This auxiliary system is often used in modern diesel direct injection engines where the standard exhaust and emission treatment systems do not suffice to reduce harmful compounds to a negligible level. Recent improvements were made to this system, such as the experiment in [40], where the amount of the SCR additive layer was successfully measured based on absorption spectroscopy, as presented in Figure 7.

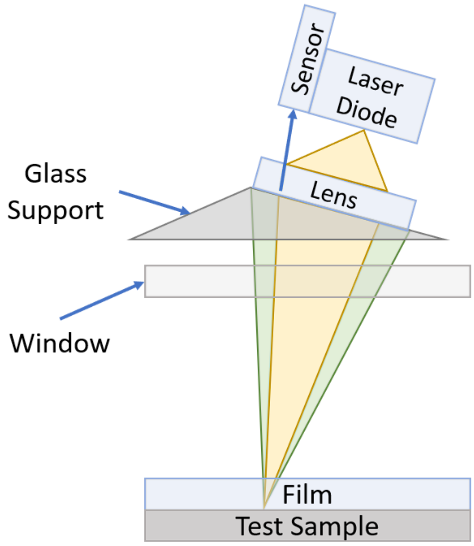

Figure 7. Measuring the SCR additive thickness using spectroscopy. The colors represent the following: Yellow represents emitted and reflected laser radiation, being detected by a sensor afterward, green shows laser radiation not detected by the sensor, while the light blue layer above the test sample represents the additive layer.

Such additional exhaust control systems would further decrease harmful chemical compound quantity while achieving a greater chemical decomposition efficiency using a process-controlled additive delivery system. However, as will be discussed in further chapters, the logistics of adapting such systems to renewable technology would be too great, resulting in many disadvantages in contrast to fully electric vehicle approaches.

3.4. Improving Renewability of Direct Injection Fuel Systems

Renewable-fuel engine prototypes emerged to mitigate the long-term negative effects of fossil fuel internal combustion engines. Various fuel blends, such as ethanol and diesel fuel mixtures, were tested during several studies, as mentioned in [41]. This resulted in decreasing several exhaust system by-products and increasing other compounds. For example, as shown below in Figure 8, this experiment reduced the carbon monoxide emissions in most scenarios.

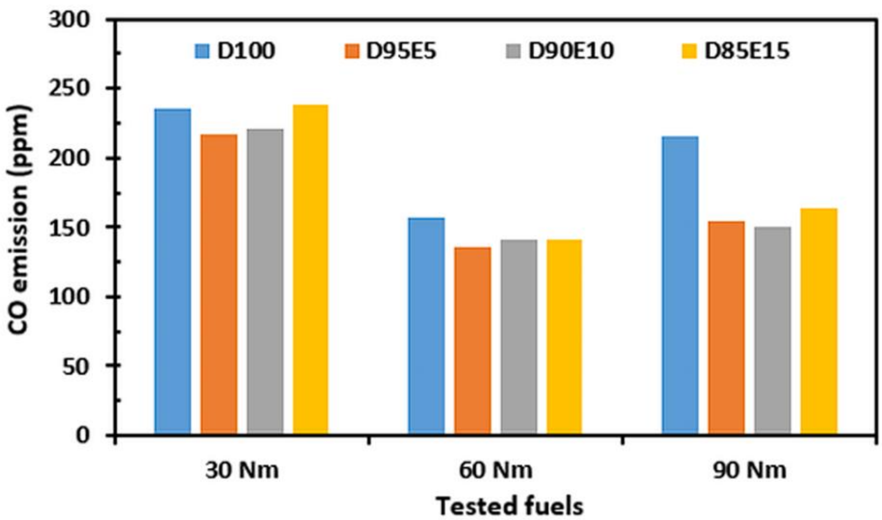

Figure 8. ICE exhaust gas emission characteristics for diesel fuel (D100) and diesel fuel ethanol blends (D95E5, D90E10, and D85E15), each showing diesel percentage followed by ethanol percentage [41]. The carbon monoxide emissions were reduced for certain fuel blends.

Additionally, further studies mention in [42] a similar situation for crude palm oil blends. Although some fuel blends increase carbon monoxide quantity, other reaction products, such as nitrous oxides and hydrocarbons, were reduced, improving CRDI engine combustion characteristics. Similarly, dimethyl ether or biodiesel and hydrogen combinations improved performance, as mentioned in [43,44]. The hydrogen addition reduced all three harmful exhaust compounds while decreasing the brake thermal factor, improving engine efficiency.

Adding crude palm oil resulted in a trade-off in emission and performance characteristics. A change in fuel properties also results in a change in CRDI engine performance, having various percentage biofuel mixtures being tested and resulting in a different performance for each study [44,45]. For example, adding the decarbonizing additive to the PB20 fuel mixture resulted in lower efficiency, as shown in Figure 9.

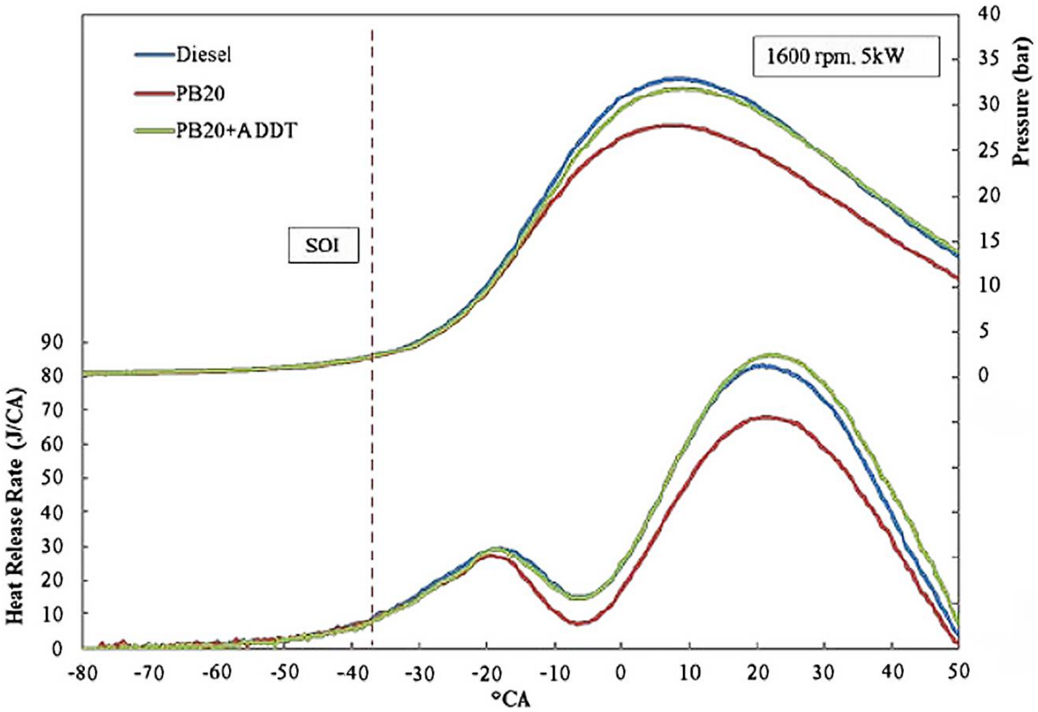

Figure 9. HRR (Heat Release Rate) characteristics for different fuel blend types, such as 100% diesel, 20% palm oil (PB20), and 20% palm oil and decarbonizing high-performance additives (PB20+ADDT) [45]. The HRR chart shows a significant improvement in engine efficiency when substituting diesel with PB20 and a small improvement when replacing diesel with PB20 and additives.

The overall engine efficiency can be measured by evaluating the heat released during engine operation using a factor known as HRR. A greater amount of dissipated heat leads to decreased engine efficiency and increased consumption for achieving propulsion at a constant speed for a given vehicle load. A lower amount of dissipated heat results in greater engine efficiency for the same load. Also, a different efficiency characteristic would be obtained by changing the cylinder compression ratio [46].

However, despite most ICEs sharing the benefit of being robust but not sustainable, several mechanical components will become prone to early failure when attempting to provide an immediate renewable solution. This happens because operating the machinery beyond the maximum ratings using such fuel blends for increased sustainability. As discussed in the next chapter, the renewability of CRDI engines decreases during prolonged operation with renewable fuels.

3.5. Known Renewability Issues and Reliability

As oil reserves decrease, biofuel blends can extend the already available fuel quantity, increasing sustainability. Due to the increase in biofuel percentage in high-pressure fuel systems, all the components become prone to excessive deterioration. This happens because the friction between mechanical components increases when a certain fuel is used as a lubricant, which is different from the one designed for this mechanical system.

As reviewed in several studies, by evaluating the properties of conventional biofuels, these are prone to absorbing and retaining more moisture than pure diesel fuel. One study, by performing turbidity experiments, found that in temperatures ranging from 10 to 50 °C, biodiesel fuel retained up to 10–15 times more water than diesel fuel. Moreover, at constant relative humidity, the biodiesel fuel absorbed 6.5 times more humidity, and the long-term operation of such systems resulted in deposit formation [47,48]. The change in fuel coefficient of friction also represents a concern [49] because modern diesel engine transportation systems use solenoid or piezo injectors and operate up to 2000 bars [50], requiring high precision and reliable components.

Researchers conducted studies to evaluate water contamination in conventional biological fuel mixtures. The testing method involved procuring the biofuel (in this case, crude palm oil) from different suppliers, followed by mixing it with pure diesel fuel. Different fuel blend ratios were evaluated for moisture content at the Sucofindo Padang Laboratory. Fuel blends are named based on the biofuel content. For example, a B5 fuel blend denotes a 5% crude palm oil content, while the remaining 95% represents diesel. The following data were extracted from these studies, presented below in Table 1, obtained through the ASTM D6304 standard test method for determining the entrained water in petroleum compounds [51,52].

Table 1. Crude palm oil water content in different biofuel and diesel mixtures [51].

Biodiesel Blend	Water Content [mg/kg]	Water Content above Limit
B5	85	No
B10	111	No
B40	416	No
B50	560	Yes
B100	1300	Yes

Studies also show the corrosion effects on injector nozzles using renewable fuel in direct-injection engines. The fuel type used in this research was Jatropha biodiesel fuel, for which multiple metal plates were fully emersed into different fuel blends. Four fuel blends were evaluated, starting from B0, where almost no corrosion occurred. B25 fuel blend shows a significant increase in rust stain occurrences, followed by B50 and B100 types, which show even more advanced oxidation on their corresponding test plates [53].

Figure 10 shows the corrosion rate characteristic for an injector nozzle material based on SEM (Scanning Electron Microscopy). As discussed earlier, despite having a specific blend offering better engine performance and lower harmful exhaust gas emissions, the higher the renewable fuel percentage, the greater the corrosion on high-pressure injection system components.

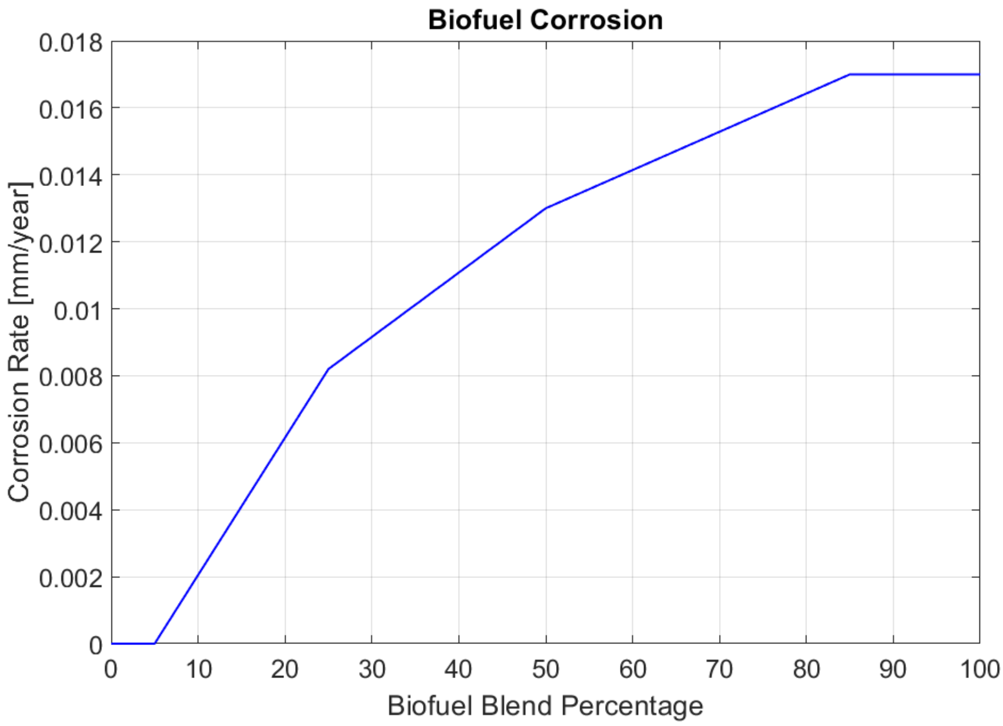

Figure 10. The corrosion rate in millimeters per year (mmpy) as a function of biofuel percentage. Corrosion increases logarithmically as a function of biofuel percentage due to the hygroscopic properties of biofuels, highlighting the immediate component degradation above 5% palm oil.

A study aimed to evaluate the injector performance for W/D (Water-in-Diesel) emulsified fuels at the SU KWANG Precision Co. Korea testbench, investigating the long-term degradation of such components. W/D blends, despite being a cost-effective solution in providing a renewable option for ICEs, show poor lubrication, which led to the degradation of internal fuel delivery control mechanisms for all injectors [54,55]. The typical structure of an injector is shown below in Figure 11.

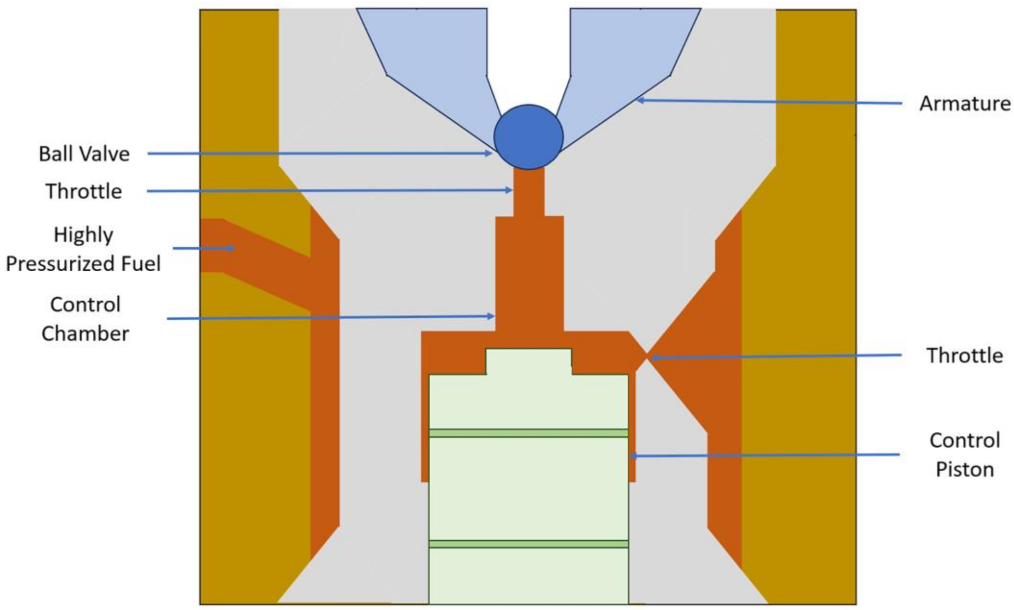

Figure 11. Side view of a solenoid injector used in CRDI systems.

The performance of such components can be evaluated by measuring the back-leak quantity of fuel. During testbench studies, the experiment has shown a reduction in injector performance by up to 6 times. The ball valve no longer accurately controls the amount of delivered fuel, leading to improper combustion cycles.

Moreover, a more critical component is affected by corrosion for higher biofuel concentrations. Because the main propulsion mechanism of HEVs is still the internal combustion engine, the HPFP (High-Pressure Fuel Pump) is critical in maintaining the engine operation. Such a component is often lubricated by its fuel. Being driven by a timing belt or timing chain, the HPFP transforms a rotational motion into a translation needed to maintain the fuel pressure in the rail. Often, tolerances are very small, and by increasing the water content in fuel, degradation happens at an accelerated rate.

At a certain point, the corrosion effects become more significant, which will often cause the complete failure of a CRDI fuel system. This is due to contaminating the fuel with metal fragments from any degrading component, propagating further to other parts, and corroding or degrading most of the HPFP working components.

As shown in Figure 12, after a CRDI fuel system failure, all parts of the fueling system must be removed and cleaned or replaced, leading to a significant repair cost. The root cause of HPFP failure is poor-quality fuel and increased water content, which compromises the structure of working parts. This is directly related to using biofuel blends in systems originally designed to use fossil fuels, and such systems are often unable to tolerate the increased water content, as well as a different viscosity or lubrication coefficient [56,57].

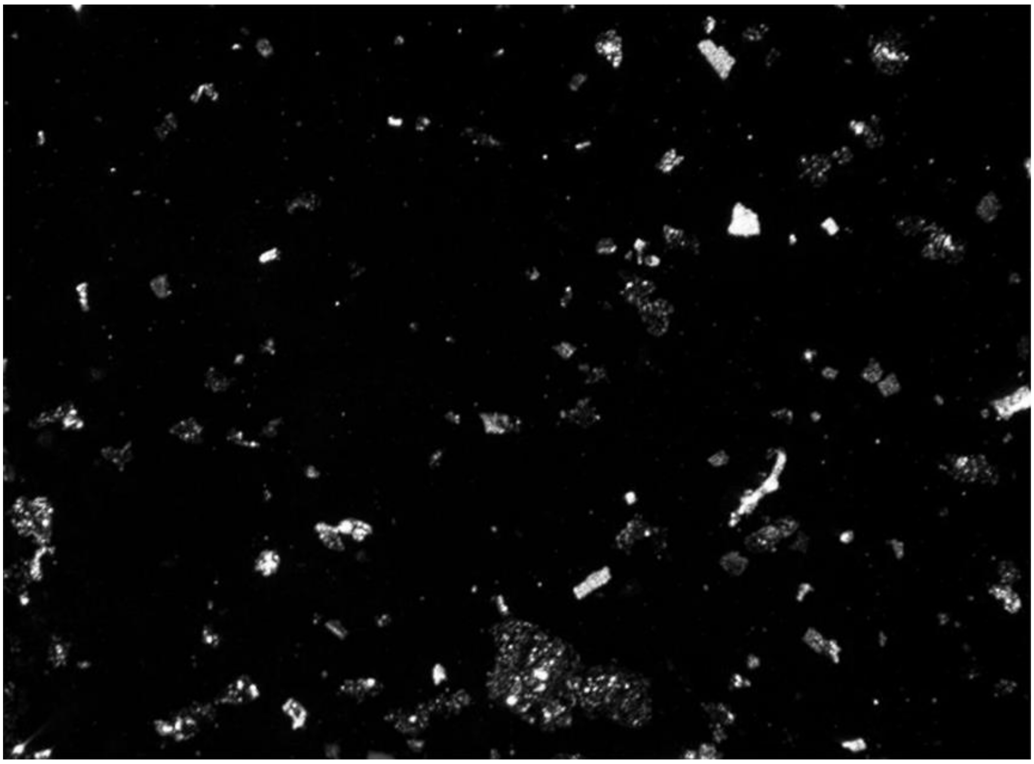

Figure 12. Fuel contaminated with metal fragments [56].

According to statistics, most of the working parts of HPFPs can be identified as prone to frequent failures, as shown in Figure 13.

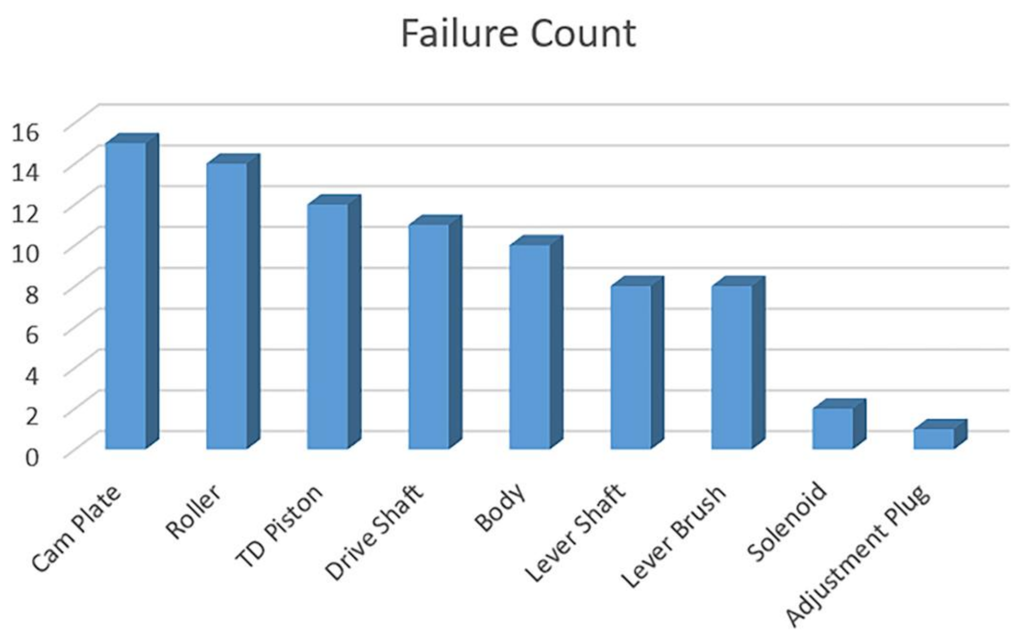

Figure 13. Occurrences of HPFP component failures show most of the failures occurred for motion-translation components.

Similar to the previous situation, this study mentioned the water intrusion inside the fuel line as the main cause of HPFP component failure [58]. In each case of fuel pump failure, the vehicle becomes no longer operational without maintenance. In most cases, this would involve replacing the entire fueling system due to contamination by metal fragments, such as the fuel tank and high-pressure fuel rail system.

Considering all studies, constraints, expected effects, and future trends, ICE-based transportation solutions are further analyzed for their robustness and renewability, as described in Table 2. The first research case was already covered because of the ICE vehicle evolution, while the second covers the possible outcome of relying on biofuel mixtures. The last scenario studies the impact of biofuel production on infrastructure.

Table 2. Robustness and renewability analysis for ICE-based vehicles.

Research Topic	Advantages and Compromises	Expected Effect	Future Directions
1. Use of direct injection systems for all future transportation vehicles [1]	Robustness increases, sustainability changes based on fuel type	Improved combustion control, health concerns mitigation	Designing mechanical components for new vehicles and fuel types [3]
2. Biofuel percentage increase in high pressure injection systems [1]	Sustainability increases, robustness decreases	Unexpected and frequent vehicle failures [3]	Expansion of biofuel crop areas, recall of in-service vehicles [3]
3. Greenhouse gas reduction through intense biofuel use [2]	Sustainability increases, infrastructure development decreases	Commitment to zero emissions	Non-sustainable resource depletion, significant agricultural changes, biosphere degradation [4]

[1] Corresponds to vehicles. [2] Corresponds to changes related to energy infrastructure. [3] Confirmed by study. [4] Confirmed by [59].

Overall, the future trend for this transportation solution would be adapting all fuel delivery components to tolerate the water content from sustainable fuel mixtures. However, this would require rare-earth materials that are resistant to corrosion and friction, similar to iridium, tungsten, or titanium.

Currently, considering the EU (European Union) commitment, if no change in renewable fuel crop land happens, the greenhouse gas emission reduction will not meet the savings required by the EU Renewable Energy Directive [60]. Therefore, to further approach the commitment, an expanse of the available cropland for biofuel production will be required to compensate, a factor constrained by the population increase and ongoing climate issues. A greater fertile farmland area imposes deforestation [59], further affecting climate regulation and possibly not mitigating the increasing weather severity and adverse events. Also, the control unit software and exhaust treatment systems would have to be adapted for the change in harmful exhaust gas components in the event of only using renewable fuels because these fuels result in different combustion constituents.

Considering the SDG (Sustainable Development Goal) target, converting the ICE vehicles to a sustainable solution would not provide an affordable and reliable transportation means (SDG7), limiting the economic growth due to land use (SDG8), further enhancing deforestation and not preserving natural ecosystems (SDG13) [61]. The inequalities of rural areas, income, and travel time influence the decision to maintain the transportation infrastructure in its current state [62], highlighting the currently increased percentage in ICE vehicle sales [61]. Also, for ICE engines, the average operating energy in kilojoules per passenger-kilometers is approximately 4 times higher than electric vehicles at the same average speed [63]. Being reliable and providing an extended travel range, this non-sustainable transportation solution might still be manufactured for 20 to 30 years in the future [64,65].

Combined with the hypothetical expansion of biofuel crop farmland and the increase in vehicle manufacturing and maintenance expenses, as well as considering the SDGs not completely fulfilled, it is uncertain whether this solution will provide a robust and renewable transportation infrastructure. This also applies to hybrid-powertrain vehicles because the same main propulsion mechanism is being used here, namely the ICE, which is mostly affected by all these constraints.

4. Electric Vehicles

4.1. Battery-Powered Topologies

Fully electric vehicles no longer use the widespread internal combustion engine from conventional vehicles and hybrid drivetrains. These vehicles are equipped with a high-voltage battery package, usually lithium-ion, lead-acid, or nickel-metal-hydride, using an inverter as a conversion circuit. The voltage and current delivered to this motor are adjusted to the predefined values during driving. A basic schematic is shown below in Figure 14.

Additional features, such as regenerative braking, were typically implemented in electric vehicles. Based on system design, this energy recovery mechanism converts momentum into electrical energy through magnetic circuits, allowing the user to recover all or a certain percentage of this energy.

In contrast to using a gearbox to increase or decrease the electric motor torque, integrated motors in vehicle wheels also became available to minimize production costs further [66].

The power controller, in this case, could also monitor the state of health of the electric motor based on transient signal characteristics and pulsed operation measurements [67,68].

Onboard electric chargers were developed to convert grid AC into DC at a constant charging rate specified by the high-voltage battery pack manufacturer. This charging system became integrated into the vehicle electric network, and based on the safety standard, it could consist of galvanic separation, delivering charging powers between 3.3 kW and 22 kW [69]. The AC conversion circuit usually consists of a high-voltage PFC (Power Factor Correction) boost converter or a totem pole PFC topology, different for each design, followed by high- to low-voltage conversion circuits, such as a forward converter, a flyback converter, or push-pull topologies. More efficient circuits like resonant converters are more suitable for high-power and high-efficiency onboard chargers.

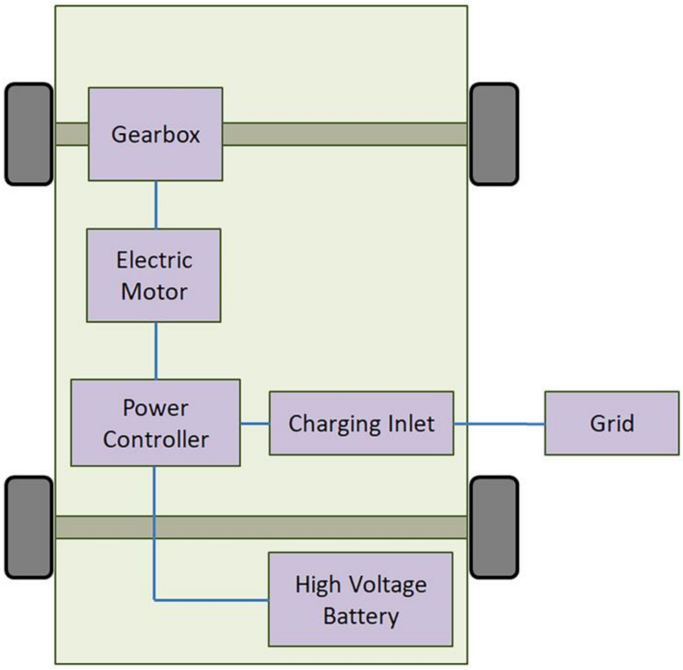

Figure 14. EV (Electric Vehicle) block diagram.

For high-energy-density applications, where EMI (Electromagnetic Interference) and switching losses need to be minimized while maintaining a high-efficiency percentage, the zero voltage and current topologies have proven to be a suitable solution [70]. By switching the execution elements during oscillations caused by resonance, zero voltage and current occurs at a certain moment, for which switching losses become negligible.

Zero voltage and current switching were also successfully implemented for improved PFC circuits, such as the totem pole converter. However, as mentioned in [71], during transistor switching, current spikes may cause certain problems related to electromagnetic interference for this AC charging circuit, with its basic diagram shown below in Figure 15.

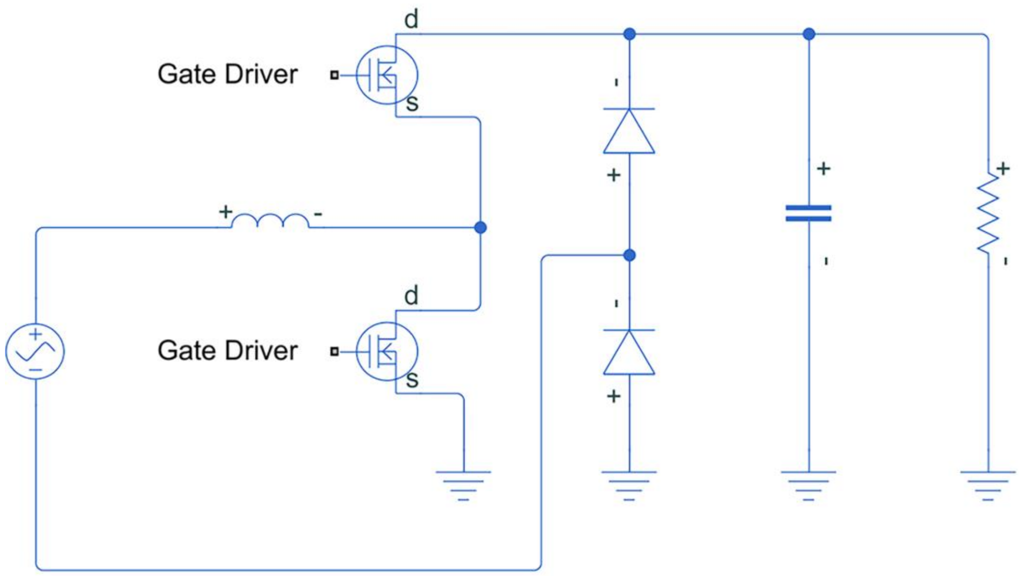

Figure 15. Totem pole AC to DC converter circuit.

Interleaving this type of converter allows for the development of even faster charging circuits while also needing improved control strategies to mitigate the switching electrical noise. Coupled inductors were used for this purpose but designs for multiple phases still must be researched to improve performance further [72].

4.2. Energy Storage and Transfer Systems Advancements

With the recent advancements in electrochemical lithium extraction techniques involving several materials for working electrodes [73], lithium-ion rechargeable batteries have become one widespread option in EV energy storage systems.

Using an analog-to-digital measurement and monitoring circuit, namely the BMS (Battery Management System), the EV control unit takes measurements regularly, and based on a predictive algorithm, it is possible to determine the remaining travel range or other battery pack parameters [74,75]. Different battery types became available for the energy storage system [13], with their specifications shown below in Figure 16.

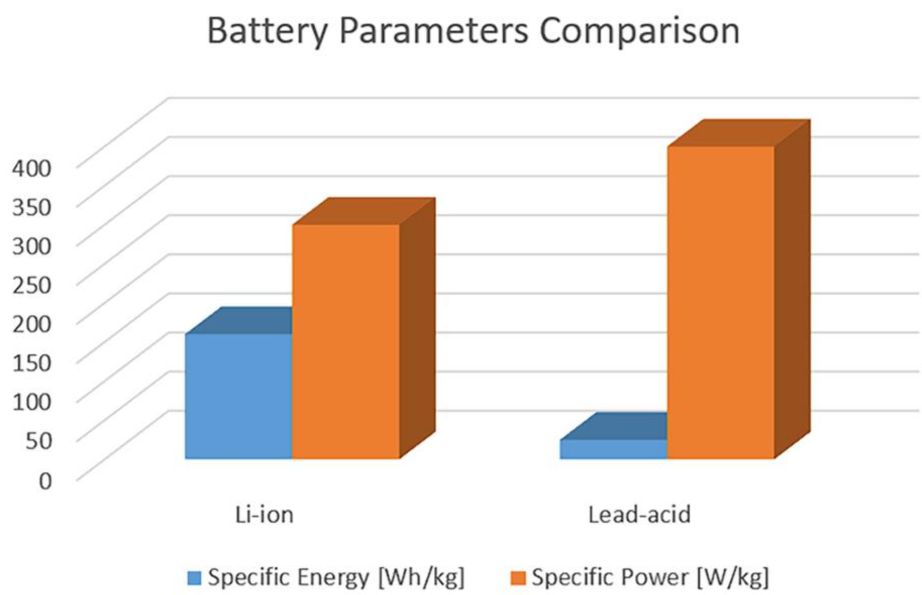

Figure 16. Comparison of lithium-ion (Li-ion) batteries to lead-acid.

Because the former battery type covers a greater range of benefits than the latter, efficiency improvement and lithium-ion battery packs became an option in a significant percentage of modern EVs. Nevertheless, researchers have achieved lower consumption-related battery pack losses for a new type of rechargeable battery described in [76].

Additional charging circuits could be implemented for EVs, such as including solar panels over certain sides of the chassis. During the most favorable climate conditions, this charging system can deliver power of up to 50 watts per hour, allowing the battery pack to recharge further [77]. The diagram describing this charging system is shown below in Figure 17.

The provided charging energy is negligible compared to the total battery pack storage capacity. Charging the EV only by this means would require a very long time to finish, increasing the vehicle complexity with an additional maximum power point detection and an energy conversion circuit.

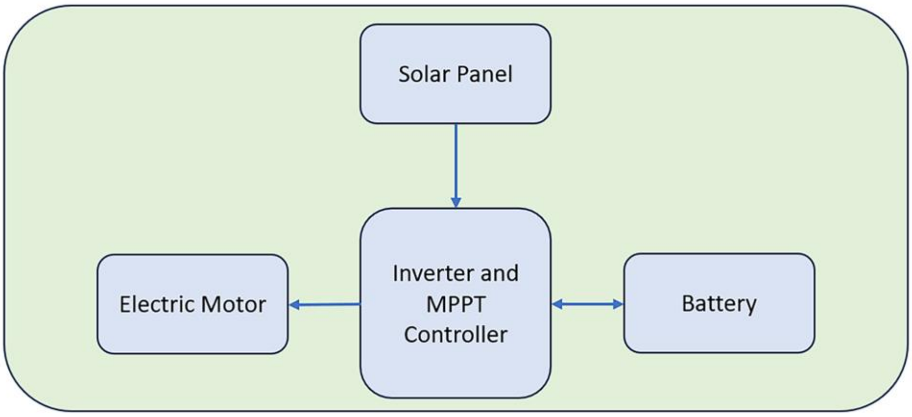

Figure 17. Solar panel charging system integrated into an electric vehicle.

However, as a possible replacement for the previous energy transfer system, the V2G (Vehicle-To-Grid) topology was developed as an alternate way of storing and releasing electric energy, with the block diagram shown below in Figure 18.

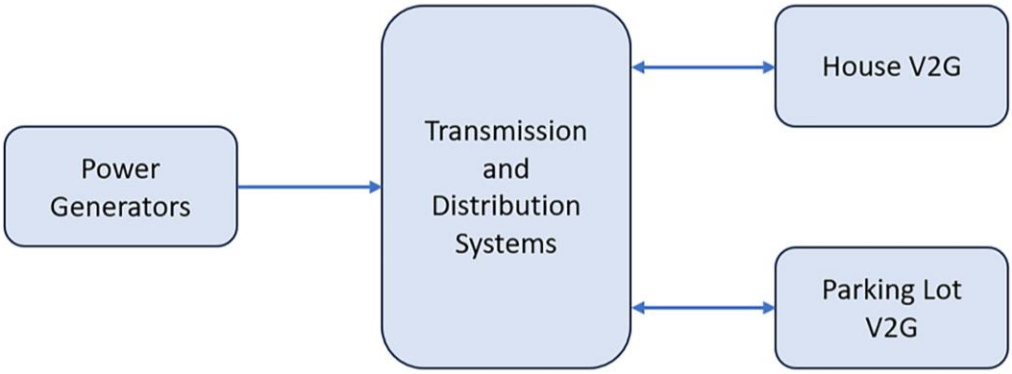

Figure 18. Vehicle to grid block diagram.

Depending on the design, for derived V2G circuits, during the day, the vehicle can charge its battery pack using a solar panel inverter, while during the night, the battery pack could convert DC to AC to power the grid and all consumers connected to it [78].

4.3. Fuel Cells for Electric Vehicles

Due to a difference in the charging stations spreading and the current state of development in some regions worldwide, the use of electric vehicles has become limited in contrast to existing transportation solutions. Based on a similar premise, researchers successfully developed an alternate energy storage and release system that converts hydrogen gas into a flux of electrons, namely the fuel cell system, as shown below in Figure 19.

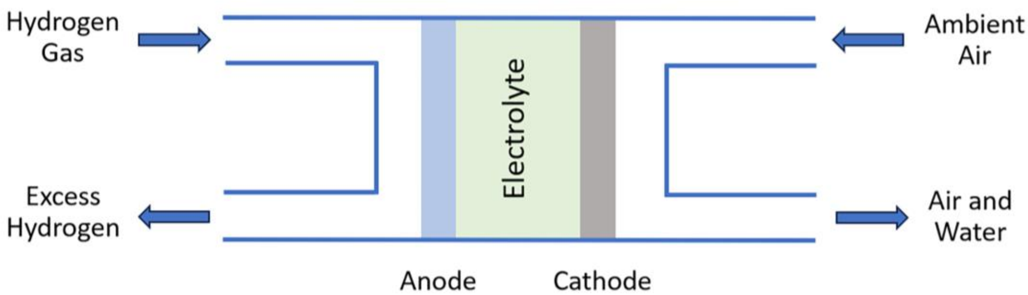

Figure 19. Fuel cell oxidation system.

Similar to standard internal combustion engines, the oxidation of hydrogen takes place. This oxidation, in turn, releases electrons at the anode, recovering the excess gas using complex regulation systems. While it represents a suitable renewable option for standard road vehicles, this system has also proven to be an option for vehicles based on research studies [79].

A major advantage of FCEVs (Fuel Cell Electric Vehicles) is the extended travel range, refueling time, and non-harmful, non-polluting exhaust emissions. Refueling time for such prototypes has been reported to be as fast as 10 min, competing directly with fossil fuel engines and being negligible to the total charging time of electric vehicles. Presently, the maximum travel range achieved by this vehicle type reaches over 450 km [80]. As for fuel consumption, road clearance studies have calculated an average for three and six cycles, resulting in around 1 kg of hydrogen every 100 km with a deviation of 1% [81]. This value depends on vehicle parameters and load, as well as all the electric devices enabled, meaning that this travel range can change in different road and climate conditions, similar to standard battery-powered electric vehicles.

4.4. Challenges and Limitations

Due to increasingly stricter safety requirements and renewability topics, basic electric vehicle concepts are currently changing. As a recent safety requirement, the electric motor of such vehicles has to be used as a line transformer during the AC charging process, which would further increase the complexity of onboard charging circuits [82]. Increased system complexity increases the error occurrence ratio, requiring updating the associated hardware tests to validate the safety part and minimize risks, resulting in more test access points and stricter error checks.

Climate conditions substantially influence electric vehicles' range due to the influence of temperature on total battery capacity. As reviewed in several studies, providing accurate values for the SOC (State of Charge) and SOH (State of Health) for vehicle management systems has proven to be a difficult issue by taking into consideration temperature change, battery aging, and misbalance between different battery parallel stacks [83,84]. Since the monitoring system in some designs is assumed to measure an LTI (Linear Time-Invariant) process, the resulting algebraic loops would cause an internal variation in systems similar to the Luenberger observer [85], leading to a loss of accuracy in both continuous and discrete domains.

Other limiting factors for electric vehicles include the travel range and the PM (Permanent Magnet) motor material availability [86,87], for example, the materials used in manufacturing neodymium magnets. The loss of active lithium has been reported as a main cause of battery pack capacity reduction [88], but other factors also influence the battery pack SOC and SOH, ultimately affecting the vehicle range over the in-service period.

Recalls occurred due to typical issues related to the ongoing research of electric vehicles [89], such as battery pack runaway due to operation outside the nominal parameters. As with all prototypes undergoing research studies, fuel cell electric vehicles are not yet mass-produced and are insufficiently refined compared to standard internal combustion engines to avoid such recalls. The availability of charging stations for electric and hydrogen vehicles also determines the decision to acquire such a vehicle.

Also, due to the switching DC-to-DC circuits used to convert the high voltage of a battery pack, electromagnetic interference will occur in various sections of the circuit [90]. Research studies have shown that certain components' input and output sides can propagate this interference [91]. These factors, in turn, limit the whole circuit design to using special communication protocols capable of withstanding these perturbations. Moreover, while minimizing the high-power conversion units, problems such as the wrong estimation of heat dissipation can occur, leading to the need to re-design certain parts.

Although the FCEV has recently received increased interest due to the extended range compared to electric vehicles [92], this technology is still under development and prone to recalls. Also, the total cost of ownership shown below in Figure 20 is only estimated to become as favorable as for BEVs (Battery Electric Vehicles) or PHEVs (Plug-in Hybrid Electric Vehicles).

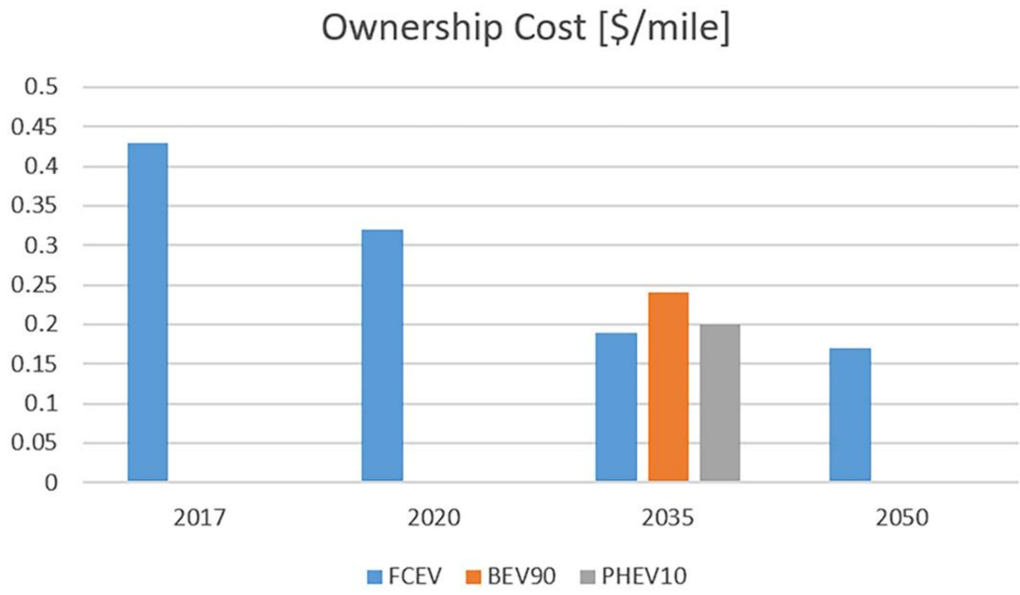

Figure 20. Estimation of ownership costs for FCEVs.

Based on this study, the ownership costs of FCEVs would become comparable to other electric or hybrid vehicles by achieving a long service life of fuel cell stacks, lowering the hydrogen cost production, and increasing production quantity [93,94]. The former factor depends on cost-reduction strategies implemented by producers, meaning that more REMs (Rare-Earth Materials), such as platinum, are required to reach an extended fuel cell stack life. Various inert metallic alloys have shown different operating times until requiring replacement, as mentioned in the intense static measurements from [95], a factor that could be used to estimate the FCEV stack life.

Studies mentioned in [94,96] analyzed the FCEV costs concerning other available vehicle types. Because the fuel cell stacks are not mass-produced, their price remains much higher than most ICE or electric vehicles. A contributing factor is the uneven infrastructure development worldwide, meaning that hydrogen refueling stations can only be found in specific areas. While considering several road transportation solutions, on average, the price of an FCEV is three times higher.

Considering the previously studied electric vehicle propulsion and energy storage technologies, a reliability and sustainability analysis is described in Table 3, covering one scenario related to vehicle manufacturing and REM depletion and another one describing economic constraints resulting from relying on green energy.

Table 3. Robustness and renewability analysis for EVs.

Research Topic	Advantages and Compromises	Expected Effect	Future Directions
1. Intensive use of REM in electric motors [1]	Robustness increases, sustainability increases	Improved energy conversion ratio, improved peak power and range	REM deposits depletion, insignificant greenhouse gas compensation through green energy [3]
2. Infrastructure expansion for electricity or hydrogen production [2]	Sustainability increases, infrastructure development decreases	More energy available for electric vehicles	REM deposits depletion, increased green energy and fossil fuel consumption for electricity production [4]

[1] Corresponds to vehicles. [2] Corresponds to changes related to energy infrastructure. [3] Confirmed by [97]. [4] Confirmed by [6,97].

The future evolution for EVs and FCEVs would increase the demand for rare-earth elements, such as neodymium for PM manufacturing and platinum for high-temperature fuel cells. Several electric vehicles are manufactured and equipped with fuel cells [98]; however, BEVs currently offer a cost-competitive solution over hydrogen-powered propulsion or ICE diesel vehicles over a 10-year ownership period, based on several additional conditions and estimations [99].

Based on the previously described hypothetical scenarios, the two proposed electric vehicles are a robust transportation solution; however, these might reach zero-emission commitment only in the future. This happens due to the significant percentage of grid energy still being generated using non-sustainable means [6] and used to either charge the BEVs or to liquefy hydrogen for FCEVs. Rare element depletion is a limiting factor affecting the deployment of such infrastructure, with only a small percentage of high-value metallic elements being recycled [100].

Therefore, the fulfillment of SDGs for these case studies is partial. Electric vehicles provide an affordable, sustainable, and reliable transportation solution (SDG7) implemented because of urgent actions to compensate for climate change (SDG13). However, the decreased energy storage capability is limiting travel range and economic growth (SDG8). Although the interest in purchasing electric vehicles is increasing [61], considering the inequality of developing areas [62], this solution might not provide a suitable option for certain customers (SDG8). Also, non-sustainable energy generation and vehicle manufacturing are factors limiting sustainability (SDG7).

The energy consumption per passenger-kilometer [63] shows a greater performance for hyperloop and railway vehicles than for electric vehicles. In some cases, such as Dubai-Abu Dhabi and Chicago–Pittsburgh Hyperloop systems, the operating energy is reduced for transporting passengers at a proportional speed, involving corresponding operating energy.

Implementing a robust and renewable transportation network in this case is plausible but not certain, because most of the energetic infrastructure uses non-sustainable means for energy generation, and REMs require energy for processing. Therefore, the study continues with extended-capability vehicles with increased passenger transportation and freight capacity.

5. Extended-Capability Vehicles

This section covers several topologies of magnetic vehicles, increasing freight transportation capability. This vehicle type maximizes the passenger or goods transport count per vehicle volume unit and operates much faster. Also, such vehicles operate on track widths similar to conventional automobiles, and supplementary safety measures were implemented to prevent hazardous events.

5.1. Magnetic Levitation Propulsion

In contrast to conventional railway vehicles, magnetic levitation trains simplify the old mechanical design and offer increased reliability and safety. The schematic of electromagnetic suspension, a functional part of this prototype, is presented below in Figure 21.

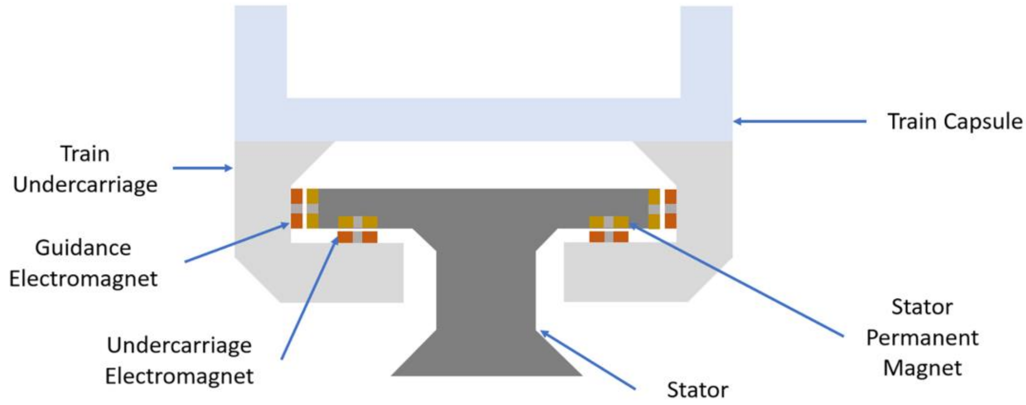

Figure 21. Electromagnetic suspension.

The electromagnetic suspension consists of inductors and coils that close the magnetic circuit through repelling, achieving levitation. The alternate variant of the magnetic levitation mechanism consists of a superconductor cooled below its critical temperature. Persistent surface currents form a magnetic field, causing the superconductor to levitate [101].

Over conventional automobiles, magnetic levitation trains typically achieve propulsion using the power grid, requiring only essential onboard propulsion mechanisms. The absence of mechanical contact between components increases the operation life while reducing operation noise and maintenance costs [102]. The propulsion and control mechanism became much more simplified than sophisticated electronic control unit networks; therefore, it is possible to implement such a propulsion system using only a conventional microcontroller and several components [103], as shown below in Figure 22.

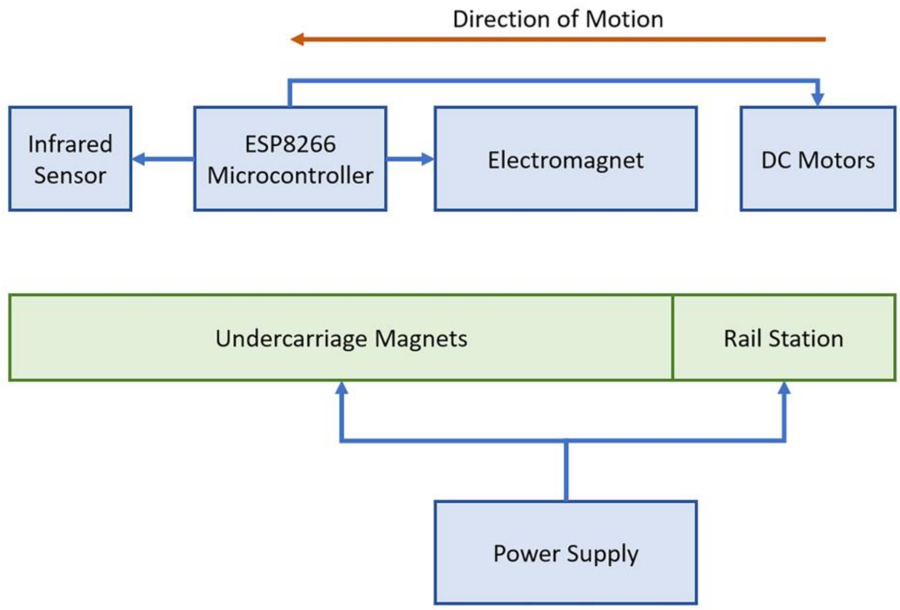

Figure 22. Electromagnetic levitation prototype.

This prototype traveled 28 cm during tests, while, as shown by the block diagram, no advanced automotive communication protocol was used. Although safety requirements would have needed to be fulfilled, this design demonstrates the functionality of such systems using a reduced-capability-embedded design and reduced hardware resources.

5.2. The Hyperloop Concept

The Hyperloop is a proposed vehicle with the potency to solve the greenhouse gas emission problems [104], achieving maximum speeds greater than magnetic levitation railway vehicles, which currently travel above 300 km per hour. By evaluating multiple criteria, this concept offers improved economic aspects and provides an alternative for air transportation systems [105]. The Hyperloop uses a vacuum tube to reduce air drag resistance as well as other necessary parts.

The prototype shown in Figure 23 uses an enclosed environment to operate in a near-vacuum regime while other structural components are added to adapt the concept to the planned track. Multiple electric compressors, typically powered by renewable energy, provide this low-pressure environment. The planned speed for future implementations reaches up to 1200 km/h [106], close to the ambient air sound propagation speed (1234.8 km/h).

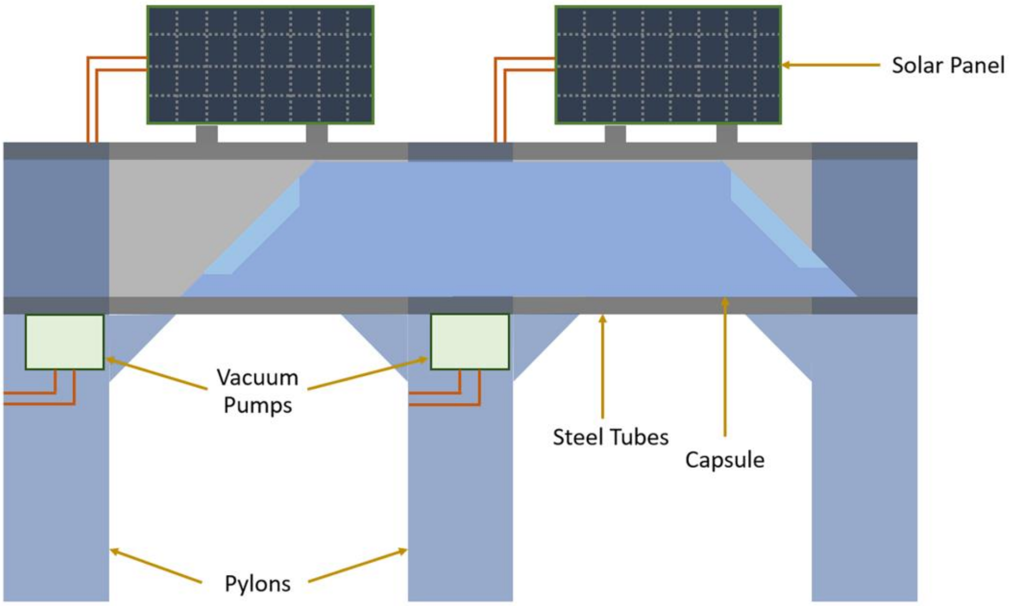

Figure 23. Hyperloop concept model.

Several advantages can be distinguished in comparison to conventional railway vehicles. This concept would typically use autonomous operation algorithms, and by having each vehicle as an enclosed capsule in a regulated environment, such systems are no longer prone to weather delays. Moreover, the Hyperloop network could be implemented only using renewable energy sources, and because of the increased velocity and greater carriage capacity, freight delivery would happen in a much shorter time. Though not yet completely evaluated, comfort is reduced due to the confined space of such enclosed capsules and may cause other temporary effects on passengers [107,108]. Compensation for this limitation would be using 3D modeling to provide various classes of comfort at a competitive price because a private vehicle might become more attractive than public transportation due to its convenience [109].

By evaluating reliability and according to [110], different failure occurrences in sensors are possible based on exposure to several materials. Being a modern transportation solution, the reliability of the hyperloop is affected by sensor quality. Extended time reliability analyses should predict the need for periodic maintenance in advance. Furthermore, the study from [107] estimated that the required time for maintenance is approximately 5 h during each operational day, possibly including the regular verification of error codes or other routine tasks.

Based on the studied vehicle functionalities and innovations, the reliability and sustainability analysis is described in Table 4, highlighting two possible scenarios related to infrastructural evolution. The first scenario considers the intense use of hyperloop in passenger and goods transport, while the second one studies the replacement of conventional transportation solutions.

Table 4. Robustness and renewability analysis for hyperloop.

Research Topic	Advantages and Compromises	Expected Effect	Future Directions
1. Intensive use of grid electricity to power hyperloop [1]	Infrastructure development increases, sustainability decreases	Shorter arrival time for freight and passengers	Increased green energy and fossil fuel consumption for electricity production [2]
2. Immediate deployment of hyperloop vehicle networks [1]	Infrastructure development increases, sustainability significantly decreases	Replacement of conventional transportation solutions	Significant non-sustainable resource depletion, immediate GDP impact is uncertain [3]

[1] Corresponds to changes related to energy infrastructure. [2] Confirmed by [6]. [3] A steady GDP (Gross Domestic Product) increase and infrastructure development is confirmed by [111].

Because a significant percentage of the grid electricity is generated using non-sustainable means, the operation of hyperloop and railway vehicles causes additional greenhouse gas emissions, increasing global temperature. In this current state, the increased use of grid energy or the immediate deployment would cause significant changes in global warming. According to [107], the hyperloop construction cost would exceed 100 million USD per kilometer. In the most favorable case, compared to the most expensive highway construction option at 950,000 USD per kilometer from [112], constructing the necessary hyperloop infrastructure over one kilometer instead of constructing a highway would exceed the highway's cost by at least 104 times. Additionally, if compared to the interquartile price range of approximately 8.8 million USD per mile of interstate road network [113] from the United States of America and based on an additional study from [114] describing the hyperloop cost at 76 million euros per kilometer, the hyperloop cost exceeds the interstate highway cost by over 14 times. This calculation excludes the land purchase for the hyperloop and considers worldwide-specific routes.

The SDGs for the two evolution directions are covered partially [61]. This reliable transportation solution could represent an affordable option (SDG7), possibly improving the infrastructure due to the decreased arrival times (SDG8). However, rural areas could not benefit from this infrastructure due to inequalities, reduced income, and distance from central districts [62]. The urgent deployment could further aggravate the climate situation due to the required energy for implementation and the part of fossil fuel used to generate energy and operate the vehicles (SDG7, SDG13).

Considering the ongoing climate events and based on the data from [63], the reduction in energy consumption for two hyperloop infrastructures in contrast to road electric vehicles represents only a small quantity. This might not overcome the generated energy using fossil fuel for operating the hyperloop combined with the resulting energy consumption from building the extended transportation infrastructure before a possible climate collapse. However, this scenario is uncertain, and an infrastructure similar to Chicago–Pittsburgh might compensate for some of the climate effects during the extended time operation based on renewable energy.

From the robustness and renewability point of view, the hyperloop is robust but currently not renewable, requiring a mostly renewable energy infrastructure to approach the zero-emission commitment, and currently remains a plausible improved transportation solution. Even though railway vehicles have specific advantages that conventional automobiles lack, the implementation cost of such a network may remain much higher than that of a road network for most countries. Also, such systems would be available only for public transportation due to the sophisticated algorithms and reduced mass-production logistics. Last but not least, from an electromagnetic compatibility point of view, a vulnerable point can be identified for both magnetic levitation systems covered in previous chapters.

6. Vulnerabilities of Grid-Dependent Power Conversion Systems

6.1. Introduction

In the hypothesis, a hyperloop vehicle infrastructure has been deployed, and major cities and less-developed areas rely on this transportation solution and a widespread electric energy grid. However, from a robustness analysis, the grid is prone to electromagnetic disturbances known as geomagnetic storms. In such an event, congestion becomes unavoidable due to the absence of a power supply. This event could last indefinitely and significantly increase economic losses; for Australia, an estimated 10 billion USD is lost annually, or 2.74 million USD is lost daily due to traffic congestion [115]. Therefore, an alternative solution for transporting energy is required to increase robustness and avoid such economic losses.

A geomagnetic storm represents a disturbance in Earth's protective magnetic field due to an intense stream of electrons carried by the solar wind. From an electromagnetic point of view, the consequences of both geomagnetic storms and pole reversals can affect modern electric circuits.

Studies have shown that, from palaeomagnetic records, the planet's magnetic poles were reversed once around 1 million years, with the reversal occurrence extending back to 1.2 billion years ago [116]. Other records, such as paleomagnetic data, show that a pole reversal occurs 3 to 4 times every 1 million years [117]. As a result of increased electron concentration and electromagnetic field perturbing, certain communication systems would become inoperable [118]. The consequences of a pole reversal are similar to a greater magnitude geomagnetic storm, affecting the main operation of magnetic levitation vehicles and the Hyperloop concept, namely the communication network and power grid.

Even though a geomagnetic storm was classified as a low-probability event, this situation poses a high infrastructural risk [119]. Such geomagnetic storms can affect modern electronics, power transmission, and communication equipment [120,121], damaging or temporarily disabling electronic circuits. Although prediction models using deep neural networks were successfully implemented [122], artificial intelligence prototypes are often prone to misleading identifications. Such situations would include falsely predicting an event or not detecting a real occurrence.

6.2. Potential Effects on Energy Infrastructure

As one of Maxwell's equations describes, the longer the conductor used to deliver electric energy, the higher the amplitude of voltage perturbances. Because of the solar wind polarization, the effects of such geomagnetic storms could be mitigated or amplified, depending on the power grid orientation [123]. Past events, such as the Carrington event from 1 September 1859, have shown the potency of these events to damage communication networks, while minor communication perturbations have been reported as early as 2022.

Without Earth's magnetic field, the magnetic field perturbations from solar wind reach the surface. The disruption comes from charged ions as electromagnetic perturbing, with electric and magnetic field vectors as components. The wavelengths of different electromagnetic radiation categories are shown below in Figure 24.

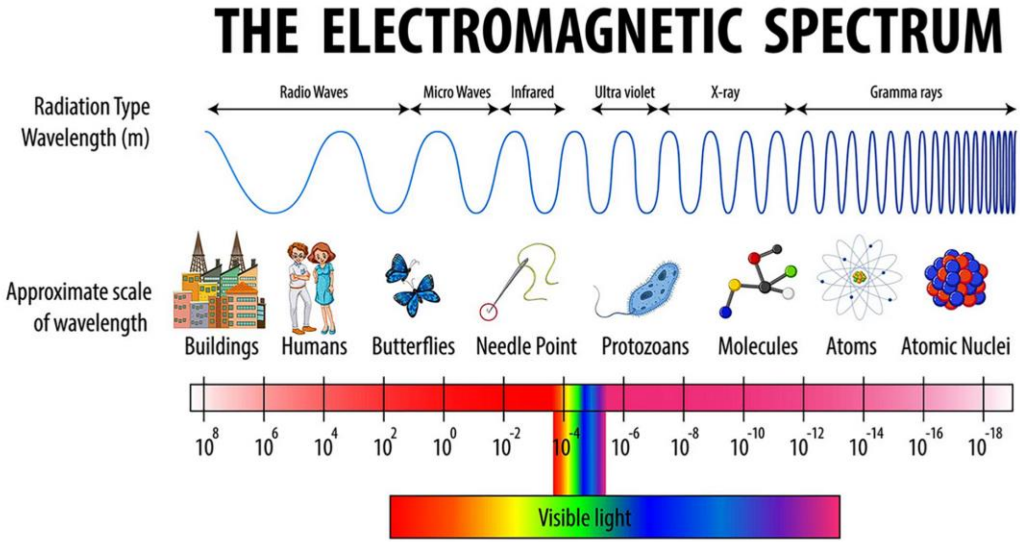

Figure 24. The electromagnetic spectrum.

An important point is represented by the solar flare and CME (Coronal Mass Ejection) emission spectrums. In the event of a solar flare, the charged particles carry only electromagnetic radiation, while for CMEs, the two factors are separated into ions and magnetic field disruption. Studies have shown that the Sun may emit gamma radiation during solar flares or CMEs [124], rendering the Faraday cage partially or non-protective against such events. Because gamma radiation may have a wavelength smaller than the spacing of the atoms, in such a case, the radiation would bypass the Faraday shielding, affecting the electric circuit that is supposed to be protected. Studies have shown that values as reduced as 10 nT per second of magnetic field disruption temporarily turned off the power line supply [125].

Although the occurrence probability of such an event remains low, the actual Hyperloop and magnetic levitation railway may not benefit from some features presented earlier during such events. Because the hyperloop relies on stator inductors energized from the grid, the main propulsion mechanism would be disabled [126,127]. Restoring physical grid supply lines also affects the necessary time to restore the transportation infrastructure [128]. Permanent magnets could be an option to increase robustness; however, rare-earth materials require intensive processing and energy consumption based on railway length [129].

Implementing wireless energy transfer conversion circuits is the solution for avoiding such situations or minimizing the impact, as well as reducing wire lengths and using integrated circuits, such as ASICs (Application Specific Integrated Circuits). In the absence of physical conductors, the effect of a CME would be minimized. Depending on severity, a geomagnetic storm may affect only a small part of the power grid, and maintenance could easily cover the affected area [130]. However, grid loads are distributed, and the uneven energy transfer may propagate problems in functional sections; the consequences of the absence of grid energy would possibly involve restricting economic development by disabling the transportation infrastructure as well as most of the essential utilities. The electric power grid is a critical infrastructure in most countries, and its capability to remain operational after perturbing events should be improved to prevent consequences related to the transportation sector [131–133]. The improvement in the actual circumstances would involve an enhanced energy management system distributing power as required by certain sections connected to the energy grid.

When establishing such transportation networks on any planet or outside the Solar System, the studies show that, even when shielded using a Faraday cage, the actual magnetic levitation designs could be affected by electromagnetic perturbing. Studies have been conducted to develop wireless energy transfer circuits for electric vehicles, and this topic is still being addressed.

7. Advances and Concerns Related to Electric Vehicles

Human operators' presence for periodic maintenance is required in all transportation infrastructures; while providing a sustainable solution with EVs network, each vehicle needs servicing to maintain its robustness. Parts, such as reactive components from converter units, namely electrolytic capacitors, require periodic replacement [134]. Other components, such as microcontroller PCBs (Printed Circuit Boards), are prone to EEPROM (Electrically Erasable Programmable Read-Only Memory) decay and data loss [135].

As fossil fuel is mainly used in generating energy [6] and biosphere degradation remains a concern due to terrain expansion [59], wireless energy transfer could be an immediate solution for substituting the current transportation infrastructure for a robust and renewable solution. When migrating an entire transportation infrastructure to wireless energy transmission, periodic maintenance of energy transmitters, for example, orbital space stations, would be necessary [136,137]. This requires the operator's presence, and health becomes important in maintaining the robustness of this hypothetical sustainable transportation infrastructure.

Nowadays, multiple health concerns are related to the effect of conversion units, typically used in electric vehicles and other hybrid and modern combustion engine means of transportation. These units cover both wire-based and wireless energy transmission. As covered in further sections, several already implemented features of vehicles could negatively impact the operator's health because such features are mainly based on wireless energy transfer, while other functionalities cause EMI perturbation.

7.1. Modern Features of Electric Vehicles

Besides the partially renewable feature of electric vehicles, producers have implemented various additions to facilitate several aspects of operation and communication, as shown below in Figure 25.

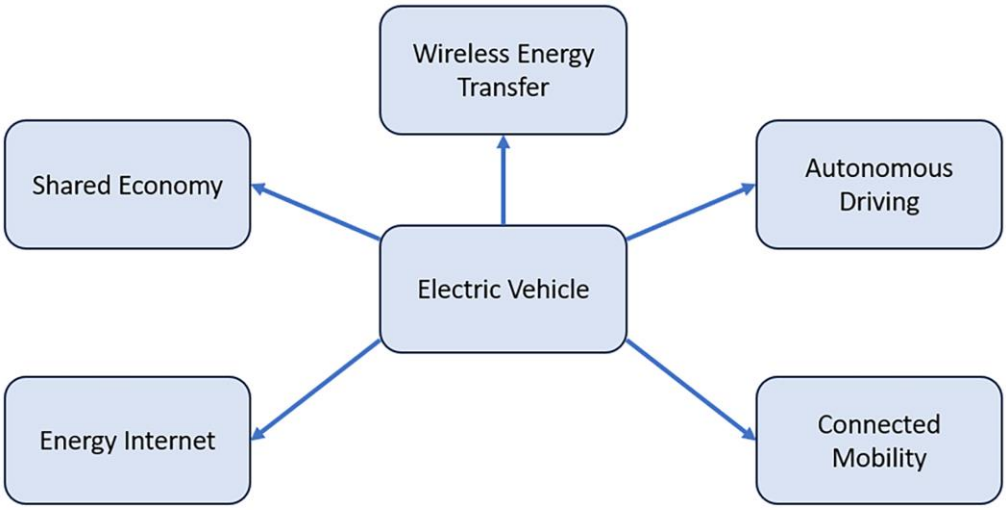

Figure 25. Innovations for electric vehicles.

The wireless power transfer concept only closes the charging circuit through magnetic coupling. As its name suggests, autonomous driving involves the possibility of driving such vehicles partially independently from the driver's commands by taking measurements of the surrounding environment. Connected mobility connects automobiles to various traffic objects, such as other vehicles, stations, or traffic signals. The shared economy concept represents the possibility of sharing operating resource costs, while the energy internet unifies the energy infrastructures (electric, transportation, or thermal) into one platform [138].

Although these systems provide utility to vehicles in production, many features are based on WiFi (Wireless Fidelity) technology. Such wireless transmission systems have been researched to have adverse biological effects. As will be discussed, even short-intensity radiation could negatively impact health during prolonged exposure.

7.2. Wireless Charging Systems

Wireless charging energy transfer has become a popular alternative to conventional inlet-plug charging systems and underwent intense studies about integration into the infrastructure [139]. Because wireless charging is more environmentally and user-friendly, switching to WPT (Wireless Power Transfer) may be a better option [140]. A block diagram for such energy conversion systems is presented in Figure 26.

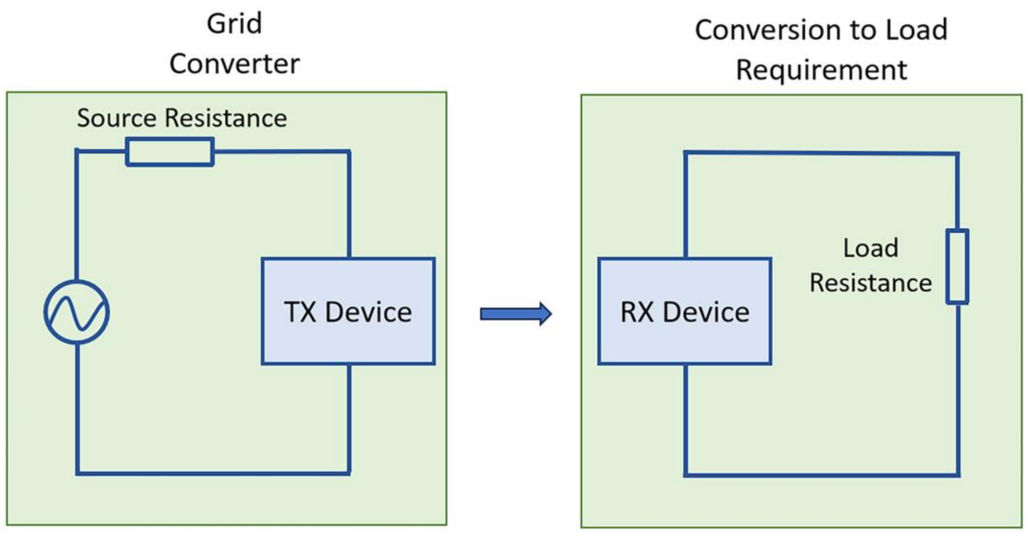

Figure 26. WPT charger block diagram.

The WPT system provides several advantages in contrast to wire charging. This charging topology does not require a physical connection between the vehicle and the station, providing a safer and, in some cases, more efficient charging circuit [141]. Moreover, certain standards offered compatibility between different chargers [142], allowing the use of charging stations to a wider extent for electric vehicles.

As for the vehicle-to-grid concept, different adaptation methods could be used to integrate a WPT system into such a circuit [143]. This would allow a bidirectional energy transfer, further extending the capabilities of such charging topologies by charging or providing energy at certain times. However, when applied to vehicles in traffic, a wireless charging system based on magnetic coupling requires an accurate alignment between the vehicle and road inductors [144]. As an alternative to this limitation, microwaves could provide an alternative transfer of energy, eliminating the need for WPT methods and eliminating the need for charging stations [145]. However, the harm risk of using microwaves for energy transfer is greater, meaning that irradiation can occur and have negative biological consequences.

7.3. Health Impact Concerns for Communication Networks

Modern electronic equipment poses the danger of long-term exposure to NIR (Non-Ionizing Radiation) for all previously covered renewable and non-renewable vehicle topologies. Multiple sources of such radiation can be identified, as shown in Table 5.

Table 5. Sources of NIR and their respective frequency bands [146].

Source	Frequency Band (MHz) [1]
Digital audio broadcasting	200
Terrestrial trunked radio	390
GSM mobile phones	935
DCS mobile phones	1750
Tx 3G mobile phones	1950
Wireless networks and microwave ovens	2450
Bluetooth	2500
4G mobile phones	3700
5G mobile phones	52,000

[1] These values are an approximation for all entries.

The data presented above show the tendency to increase the frequency band as the data transfer rate increases. Television, microwave ovens, mobile phones, and most wireless communication or energy transfer circuits are sources of non-ionizing radiation. The International Agency for Research on Cancer classified this type of radiation as a possible carcinogen, meaning that even with negligible power levels, prolonged exposure to NIR cannot be neglected [147,148].

Wireless data communication occurs in most features of modern internal combustion engines or electric vehicles. The devices communicating data are often based on high-speed communication protocols, such as GPS (Global Positioning System), built-in WiFi, and radio frequency identification devices.

Studies have found that non-ionizing radiation harms human tissue, although more research is needed on electromagnetic fields emitted by mobile phones. Also, long-term evaluation of WiFi exposure is challenging, and results might be mixed with other electromagnetic radiation types. Below a certain threshold, some researchers consider NIR to be not harmful [149,150].

However, studies have shown harmful effects after long-term communication network use from mobile phones, including intracranial tumors [151]. Epidemiological reports have evaluated radiation exposures still below the ARPANSA (Australian Radiation Protection and Nuclear Safety Agency) standards originally mentioned as safe but found a possible linkage between salivary gland tumors and wireless communication [152,153]. Another possible linkage of pre-natal autism was reported as a consequence of long-term WiFi effects [154]. Limiting the electromagnetic perturbing exposure functions to maintain a safe environment for wireless communication and high-power conversion circuits, for which standards were set for switching frequencies between 3 kHz and 100 kHz [155].

7.4. Biological Effects of Wireless Energy Conversion Systems

During the studies mentioned in [156], it has been determined that cerebral spinal fluid has the highest electrical conductivity of all human tissues and fluids tested. The reference DC converter was operated at 85 kHz to achieve a wireless power transfer, and the study was conducted for a male human model. The results show the potential hazard related to the absorption of electromagnetic interference by multiple human body parts.

As for the improvement of switching parts in DC converter units, an experimental study points to the possible harmful effects of long-term exposure to low-intensity NIR. By changing the transistor types, electromagnetic compatibility can worsen [157]. As demonstrated by Fourier series decomposing, many high-frequency harmonics will be present in the proximity of DC converters. Even so, guidelines were applied to minimize the harmful impact on human health [158].

Overall, the higher the frequency of radiation, the more hazardous the long-term effect of wireless communication and energy transfer systems. An increase in data transfer rate involves an increase in switching frequency, which extends closer to the ionizing radiations domain; such radiations are proven to dislocate electrons and provide a greater health risk.

8. A Hypothetical Robust and Renewable Transport Infrastructure Network

8.1. Introduction

Based on the previous chapters, multiple advantages and disadvantages can be found by comparing the studied propulsion systems and energy management infrastructures, as described in Table 6. The purpose is to improve the sustainability of all previously described transportation solutions while maintaining robustness.

Table 6. Transportation solutions comparison in achieving sustainability.

Solution	Critical Dependency	Sustainability Requirement
1. ICE vehicles	Refined oil and biofuel production for operation	Adapting control software and mechanical components to new fuel characteristics; Expanding biofuel farmland [1]
2. Electric vehicles	Energy grid for charging; REMs for engine manufacturing	AC generation needs to approach a carbon neutral footprint; Recycling REMs
3. Extended capability vehicles (Hyperloop)	Energy grid for operation	AC generation needs to approach a carbon neutral footprint

[1] This consequence contradicts sustainability.

The least favorable case is represented by improving ICEs' sustainability during operation. The dependency of AC energy generation on fossil fuel represents a sustainability issue for the more favorable last two cases. Because the hyperloop transportation network is prone to congestion from AC grid failure, the study provided a hypothetical scenario for achieving the necessary infrastructure for electric vehicles. The resulting robustness and sustainability requirement for an infrastructure closer to the neutral carbon emission commitment involves minimizing the land use for energy generation, resulting in the need for high-energy-density applications.

8.2. Robustness and Renewability Improvement Based on Space Energy

An improved transport infrastructure could emphasize reliability and sustainability by choosing high-density, wireless power applications, minimizing the health impact. This would limit land expansion for human activities, including biofuel crops, solar panel deployment, and REM processing, limiting the global temperature increase while maintaining infrastructure robustness over a prolonged period. A possible implementation represents a distance energy transfer infrastructure from Figure 27.

In this figure, the object-fixed frame is denoted by unit vectors. $\hat{o}_i$, $\hat{o}_j$, and $\hat{o}_k$, which remain attached to the satellite and move relative to the inertial frame, are denoted by unit vectors $\hat{e}_i$, $\hat{e}_j$ and $\hat{e}_k$. Satellite trajectories can be modeled using the three-body problem, and recently, more accurate approaches emerged based on artificial intelligence [159].

Analyzing the alternate SBSP hypothetical scenario, several scenarios result in various outcomes, as described in Table 7. The first case describes the initial use of green energy for EV charging and its impact on infrastructure, while the second case covers an increase in green energy production through additional SBSP satellite deployment. The last study describes possible health degradation for operators in the hypothesis of permanently monitoring these energy transfer system components.

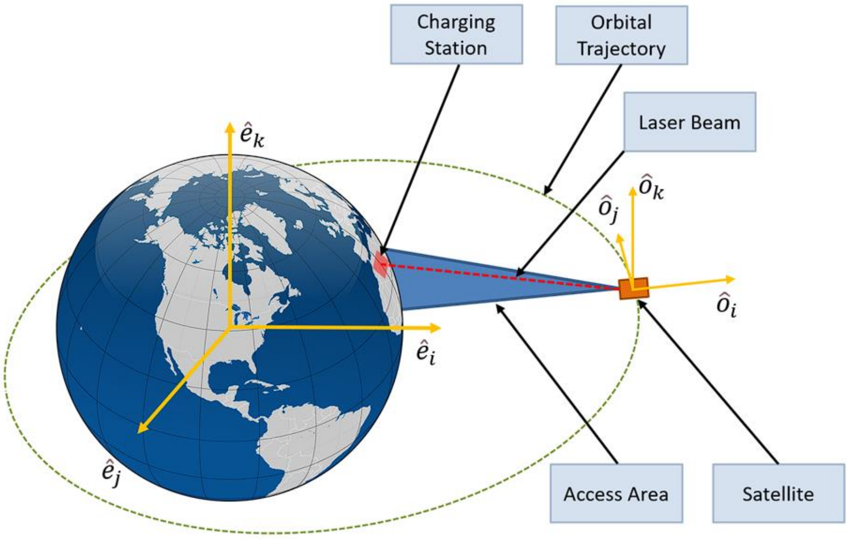

Figure 27. Distance energy transfer charging infrastructure. This approach uses an alternative SBSP (Space-Based Solar Power) transfer, storing and releasing energy using satellites on orbital trajectories. The energy is sent to ground charging stations.

Table 7. Robustness and renewability analysis for an alternative SBSP infrastructure.

Research Topic	Advantages and Compromises	Expected Effect	Future Directions
1. Intensive use of charging station energy [1]	Infrastructure development is uncertain, sustainability increases	Commitment to zero emissions	Increased availability for green energy [3,4], biosphere degradation is uncertain [6]
2. Increased green energy availability [1]	Infrastructure development is uncertain, sustainability further increases	Increasing number of SBSP satellites	Legal and territorial limitations are uncertain [4], biosphere may degrade [6]
3. Use and maintenance of high-energy conversion units for space applications [2]	Robustness increases, sustainability further increases	More effective orbital energy transfer	Operator health degradation [5], biosphere may degrade [6]

[1] Corresponds to changes related to energy infrastructure. [2] Corresponds to parts from the energy infrastructure. [3] Improved by [160]. [4] Confirmed by [161]. [5] Partially confirmed by [151,152,156]. [6] Unconfirmed plausible scenario.

As described in [161], even with the inherent increase in available power from space satellites, the applicability of this concept may impose legal challenges, such as ensuring safe operation and minimizing biosphere degradation. Additional steps might include the development of various architectures, protocols, safety concepts, prototypes, and concept verification stages. Recently, smaller-size lean satellites were successfully adapted to tolerate a regulated energy transfer typically used before in large-size satellites [162]. However, even with the recent advances, due to the lack of certainty, the economic impact cannot be accurately predicted for intensively using space-based green energy. The increase in satellite numbers may have territorial implications, and periodic satellite maintenance will require space missions. This applies to using solar energy or laser diode emitters to create energized beams to be recovered by ground charging stations.

The indefinite increase in available energy might provide a solution to mitigate the continued global warming increase resulting from ongoing human activity. To further complete this sustainable and reliable infrastructure, generic-purpose EVs can be used with charging stations and SBSP ground charging stations for passenger and freight transportation.

Reducing used land areas and using sustainable means to generate, transfer, and release energy for vehicles could fulfill the SDGs to a greater extent. Electric vehicles already present a solution regarding affordability, reliability, and sustainability [61], and in the future, the interest in purchasing EVs is expected to increase (SDG7). Consequently, urgent actions for migrating the transportation infrastructure to this hypothesis might mitigate the climate adverse events (SDG13). However, economic growth might be restricted due to the typically limited amount of green energy and territorial limitations (SDG8).

Considering that all verification stages and safety concepts were fulfilled, this solution represents a plausible infrastructure for providing a robust and renewable modern transportation network. However, deploying such infrastructure requires high-precision parts, such as the accurate collimation of emitters. This would be necessary to achieve a similar or greater transmission distance than conventional communication devices for delivering energy to the charging station.

9. Conclusions

We aimed to review the current global climate issues and several available propulsion systems in transportation networks. Immediate adaptations were studied in these modern transportation infrastructures and the corresponding constituents, highlighting sustainability and reliability, recent improvements, innovations, advantages, and related concerns. To prevent unexpected, catastrophic weather events linked to global warming, deploying a sustainable transport network is necessary, and robustness should be maintained for economic growth. After analyzing the robustness and renewability of each studied infrastructure, with the respective future directions and scenarios, global warming mitigation would be achieved using high-density energy applications.

The currently in-service ICE vehicles could not be adapted to a sustainable transportation solution without major recalls or significant environmental damage. The study has discovered the limitations of electric vehicles and the necessity for infrastructural green energy commitment to replace fossil fuel use in energy generation. Although the generic purpose of electric vehicles provides more sustainability, this infrastructure insufficiently compensates for the greenhouse gas emissions due to the non-sustainable electricity generation for charging stations.

The study expanded the initial research to extended capability vehicles to provide increased transportation capacity for passengers and freight. Although these solutions provide greater sustainability, they still rely on non-sustainable electricity generation, and the implementation cost compared to road networks is significantly greater. A vulnerability point can be identified by considering their operation on a planet lacking the protective magnetosphere or operating this vehicle during severe space events, resulting in more pronounced delays.

As future space applications are still developing, substituting the widely used wire transfer for an optoelectronics-based network could fulfill both the reliable and sustainable criteria. Also, along the distance energy transfer and communication paths, perturbations are minimized due to the reduced conductor length and wireless energy transfer, possibly allowing for continuous ground-level transportation and minimizing economic loss.

As this domain involves concentrated energy beams, zero carbon emissions could be achieved by recovering an energized beam using specialized conversion circuits involving custom-built components. This could result in minimizing land use and could settle the increasing climate temperature to habitable levels. However, this would involve researching and deploying different infrastructures, and further refinement for customized parts, prototypes, testing stages, and safety concepts must also be covered. Also, a broad range of studied concepts would be necessary for the conceptualization stage for implementing this methodology, which is a plausible, reliable, and sustainable solution to approaching a neutral carbon footprint.

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Abbreviations

IPCC	Intergovernmental Panel on Climate Change
ICE	Internal Combustion Engine
CRDI	Common-Rail Direct Injection
EFI	Electronic Fuel Injection
GDi	Gasoline Direct Injection
MPFI	Multi-Point Fuel Injection
SCR	Selective Catalytic Reduction
HRR	Heat Release Rate
SEM	Scanning Electron Microscopy
W/D	Water-in-Diesel
HPFP	High Pressure Fuel Pump
EU	European Union
SDG	Sustainable Development Goal
EV	Electric Vehicle
PFC	Power Factor Correction
EMI	Electromagnetic Interference
BMS	Battery Management System
V2G	Vehicle-To-Grid
SOC	State of Charge
SOH	State of Health
LTI	Linear Time-Invariant
PM	Permanent Magnet
FCEV	Fuel Cell Electric Vehicle
REMs	Rare-Earth Materials
BEVs	Battery Electric Vehicles
PHEVs	Plug-in Hybrid Electric Vehicles
GDP	Gross Domestic Product
CME	Coronal Mass Ejection
ASIC	Application Specific Integrated Circuit
PCB	Printed Circuit Board
EEPROM	Electrically Erasable Programmable Read-Only Memory
WiFi	Wireless Fidelity
WPT	Wireless Power Transfer
NIR	Non-Ionizing Radiation
GPS	Global Positioning System
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
SBSP	Space-Based Solar Power

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