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Review

Moving towards Greener Road Transportation: A Review

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Abstract: Road transportation accounts for about 20% of the total GHG emissions in the EU. Nowadays, the substitution of conventional fossil fuel-based ICEs with electric engines, or their hybridization, operating along with Energy Storage Systems, seems to be the most appropriate measure to achieve reductions in both fuel consumption and GHGs. However, EVs encounter crucial challenges, such as long charging time and limited driving range. Hence, the transition to the mass adoption of EVs requires considerable effort and time. However, significant steps have been taken in the hybridization of road vehicles, with the aid of renewables and energy recovery/saving systems. In this context, this paper presents a comprehensive literature review of modern green technologies for GHG reduction that are applicable to road transportation, such as on-vehicle energy harvesting and recovery (e.g., thermal, kinetic, etc.) systems and the incorporation of RES into EV charging stations. The impact of road vehicles on the environment is discussed in detail, along with the EU roadmap towards the decarbonization of transportation. Next, methods and techniques for fuel consumption and GHG reduction are systematically presented and categorized into on-vehicle and off-vehicle ones. Finally, a future outlook on more environmentally friendly road transportation is presented.

Keywords: transportation sector; Electric Vehicle (EV); road transportation; EV charging; charging infrastructure; Renewable Energy Sources (RES)

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1. Introduction

The Transportation Sector represents a great fraction of the European Union (EU)'s Greenhouse Gas (GHG) emissions. Specifically, it is estimated that it constitutes about 23% of the total carbon dioxide (CO_2) emissions [1], whereas it remains the sector with the lowest share of renewable energy use. In more detail, according to 2020 data, the Energy Sector accounts for nearly 40% of global GHG emissions, the Transportation Sector for 23% and the Buildings Sector for almost 27%, whereas the remaining 10% corresponds to agriculture, forestry and land use, as well as the chemical and cement industries [2]. In this context, the Paris agreement comprises a global framework that aims to achieve the mitigation of climate change consequences, focusing mainly on a significant reduction in GHGs. Despite the fact that the Energy Sector is gradually adopting the use of Renewable Energy Sources (RES), this is not the case for the Transportation Sector [2].

Indeed, the share of RES in global electricity generation amounted to 28.5% in 2020 and 2021, equal to almost half of the 2030 target, whereas both wind and solar power plants generated more than 10% of the global electricity [3]. In 2021, the RES capacity increased by 314 GW. However, this upward trend was not reflected in the overall energy mix, as the use of fossil fuels remains high, due to the rising electricity demand after the

COVID-19 pandemic and the reduced global hydropower generation, caused by reduced precipitation [2].

Renewable capacity is foreseen to increase by over 8% within the next two years, despite the surging prices for many raw materials and the high freight costs. This is a result of the high prices of fossil fuels (i.e., especially the significantly high price of natural gas), which determine the hourly and daily price in many wholesale electricity markets, such as in the EU [1]. In parallel, solar photovoltaic (PV) systems (i.e., mainly new utility-scale projects) are forecasted to account for approximately 60% of the installed RES capacity, whilst the capacity of offshore wind parks will be doubled, compared to 2020. On the other hand, a slight reduction in new onshore wind capacity is forecasted, mainly because of the increased investor interest in offshore wind installations, as a result of the favorable legal framework, as well as the higher expected energy yield [2,3].

As regards the Transportation Sector, which is the main focus of this work, limited progress can be reported, despite five years having passed since the ratification of the Paris agreement [2]. Apparently, Transportation is the sector with the lowest share of RES use, even though it represents a third of global energy demand. It is worth noting that it continues to rely on fossil fuel products for 91% of its final energy use, which corresponds only to a 3% reduction from the early 1970s [3–5]. The mandatory partial use of biofuels by conventional vehicles with internal combustion engines (ICEs) can be considered the only substantial step.

Taking into account that road transport is responsible for almost 72% of the Transportation Sector CO_2 emissions in the EU, many countries focus particularly on them [6]. However, the aviation industry and marine transportation are pushed aside, despite continuing to emit large amounts of GHGs. Additionally, in developed countries, where a large part of railroads have already been electrified, the expansion of metro and light rail systems has been pursued. As a result, EU countries have launched supporting policies, such as fiscal incentives, grants for the procurement of Electric Vehicles (EVs) and tax credits, in order to increase the number of All-Electric Vehicles (AEVs) and Hybrid Electric Vehicles (HEVs) on their roads. Considering that EVs are more efficient compared to conventional vehicles, a constant increase in EV sales will contribute to a reduction in CO_2 emissions, particularly in countries with high RES shares in their electricity mix [7]. Apparently, in order to determine the extent to which AEVs are environmentally friendly, it is imperative to examine how green the energy used for their charging is [8]. Hence, more and more RES-powered charging stations are continuously emerging [9–15].

In parallel, supportive measures have brought 16.5 million EVs to the roads of several countries worldwide, between 2009 and 2019, which corresponds to scarcely 1% of the global car fleet [16]. Unfortunately, even though the electrification of road transportation has increased, the decrease in fossil fuel consumption is only 1.3% for the same period of time (i.e., decreasing from 97.6% to 96.3%), proving the strong reliance of transportation on them. This fact highlights the need for broader electrification of road vehicles. Despite the technological advancement of EVs and the financial incentives that are adopted in several countries, there are still some major obstacles to deal with [17,18]. In order to acquire a better understanding of these obstacles (i.e., limited driving range because of the limited battery capacity, inadequate charging infrastructure, high upfront costs, limited EV model availability compared to conventional gas-powered vehicles and negative consumer perceptions due to misconceptions surrounding EVs), a brief description of a typical AEV is presented in the next paragraph.

Each AEV is built according to the generalized block diagram in Figure 1. According to this, an essential part of all AEVs is the Battery Pack (BP). A BP comprises hundreds of discrete cells (usually lithium-ion (Li-ion)), connected in series and parallel. By utilizing either an on-board or off-board charger, the electric power from the utility grid is converted to the optimal DC voltage and current levels, in order for the BP to be charged. To assure the health status of the BP, a Battery Management System (BMS) monitors the State of Charge (SoC) of each discrete cell of the BP and controls the charging process. Afterwards, an inverter (called a traction inverter) converts the DC power from the BP into a sinusoidal AC waveform, which is suitable for feeding the electric motor. Moreover, according to [19], several AEVs are equipped with two electric motors, one on each wheel axis, whereas an alternative power scheme has been also recorded; according to this second scheme, four brushless DC motors are utilized to separately propel the four wheels [19]. In both power schemes, the BMS monitors the Depth of Discharge (DoD) of each discrete cell, in order to prevent full discharge of the BP. If the latter occurs, the BP's life expectancy may be jeopardized in cases of repeated full discharges. Last, a second converter is used to step down the High-DC voltage (HV) of the BP, so as to supply the rest of the vehicle electric loads (e.g., air conditioning unit, infotainment system and lights) that operate with Low-DC voltage (LV) [20,21].

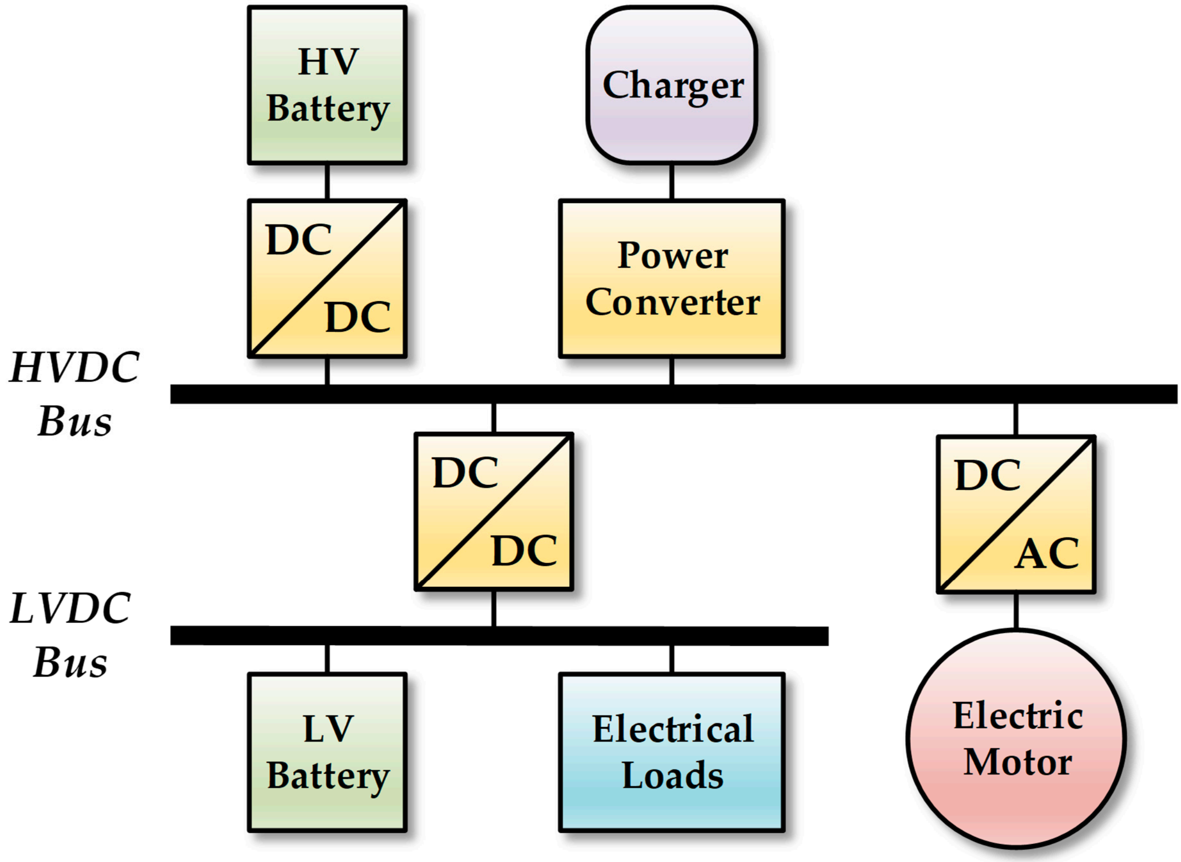

Figure 1. Generalized block diagram of an AEV.

Considering that BPs are the most expensive component of an AEV, BPs with relatively small capacities are preferred. Table 1 lists the battery capacity, the energy consumption and the driving range, according to the World Harmonized Light Vehicle Test Procedure (WLTP), of forty-one (41) of the most widely used vehicles on European roads. According to these data, the average value of the BP capacity is 60.8 kWh, the average electric range is 363.7 km, whilst the average energy consumption amounts to 157.2 Wh/km. However, in practice, the situation is slightly worse. An increase in the average speed at which the car moves, as well as the use of the air conditioning unit and the infotainment system, can increase a vehicle's energy consumption by up to 15%, leading to a drastic reduction in its autonomy (i.e., 308.9 km from 363.7 km for the studied case) [22]. By considering that nowadays, drivers are charging their AEVs as they used to fill the tank of their former conventional vehicles, it is deduced that they must wait over a prolonged period to complete a full charge, causing discomfort, especially in cases of long-distance road trips. The waiting time depends on the availability and electric power of charging points.

Table 1. Battery capacity, (WLTP) electric range and energy consumption of the most widely used AEVS on European roads.

AEV Model	Battery Capacity (kWh)	(WLTP) Electric Range (km)	Energy Consumption (kWh/100 km)
Audi e-Tron	71	336	21.13
Audi Q4 e-tron 35	52	306	18.2
Audi Q8 e-tron 50 quattro	89	410	21.4
BMW iX3	67	453	16.8
BMW i4 M50	80.7	415	18.6
DS 3 Crossback E-Tense	50	320	15.63
Fiat 500 e	23.8	180	13.22
Honda e	35.5	220	16.14
Hyundai Kona Electric	30	305	9.84
Hyundai IONIQ 6 Long Range AWD	77.4	519	14.3
Jaguar I Pace	90	470	19.15
KIA e-Niro	39.2	289	13.56
KIA e-Soul	64	452	14.16
KIA EV6	77.4	528	14.66
Mazda MX-30	35.5	237	14.98
Mercedes EQS SUV 580 4MATIC	120	511	21.2
Mercedes EQE 350 4MATIC	100	507	17.9
Mercedes EQC	80	354	22.6
Mini Cooper SE	32.6	270	12.07
Nissan LEAF	40	270	14.81
Opel Corsa-e	50	330	15.15
Opel Moka-e	50	324	15.43
Peugeot e-2008	50	320	15.63
Peugeot e-208	50	340	14.71
Porsche Taycan	93	484	19.21
Skoda Citigo E IV	36.8	260	14.15
Smart EQ fortwo	17.6	159	11.07
Jeep Avenger Electric	50.8	385	16.9
Tesla Model Y	57.5	430	16.7
Tesla Model 3	73.5	455	16.15
Tesla Model S	85	624	13.62
Tesla Model X	75	528	14.2
Toyota bZ4X	71.4	460	15.52
Volvo C40 Recharge	78	420	18.57
VW e-Golf	35.8	231	15.5
VW e-up	32.4	260	12.46
VW ID.3	45	352	12.78
VW ID.4	77	520	14.81
Ford Mustang Mach-E ER RWD	98.7	600	15.2
Dacia Spring Electric 45	26.8	230	10.9
CUPRA Born 170 kW–77 kWh	82	492	15.7

Thus, we come to the second considerable obstacle. Most AEVs can be charged either via the mains or via fast-charging points to reduce the charging time. Without a doubt, charging points should be close to an electrical supply [23–26]. Therefore, finding charging stations can be challenging on routes in mountains, the countryside or coastal and rural areas. Apparently, the situation is much easier when a vehicle moves around a city-center, where AEV or HEV owners have access to private or public charging networks. Furthermore, considering that the vast majority of people in urban centers live in flats, the above is the only feasible option, whereas domestic charging points seem impossible. Taking into account the average capacity of the above-mentioned AEV models, Table 2 presents the time needed to charge a BP, from 20% to 90% (i.e., 42.5 kWh), for three widespread types of charging point with different electric capacities (i.e., Mode I—3.7 kW_{AC}, Mode II—22 kW_{AC} and Mode III—50 kW_{DC}) [27].

Table 2. Charging time for a 60.77 kWh BP, from 20% to 90%, for three different charging points.

Electric Capacity of the Charging Point (kW_{AC})	Charging Time (min)
3.7 kW_{AC} (Mode I)	689
22 kW_{AC} (Mode II)	116
50 kW_{DC} (Mode III)	51

According to the data presented in Table 2, it is concluded that the recharge process will last from almost 45 min to approximately 11 h, depending on the available charging infrastructure. However, new charging technologies that feed AEVs with higher electric capacities (up to 350 kW_{DC}) exist [27]. However, such charging points call for reinforcement of the electrical grids and they are not yet compatible with all types of AEV [28]. On the other hand, significant effort is required in order to support the fast charging of heavy-duty vehicles. In addition to fast charging technology, the recently proposed wireless (i.e., inductive) EV charging could facilitate the charging of heavy-duty vehicles, too [29–31]. In parallel, according to [30], wireless power transfer could also assist with EV charging station efficacy by facilitating RES incorporation. Specifically, in the aforementioned work a wireless power transfer system that is applicable to DC microgrids is introduced, so as to exploit various distributed energy sources in residential or commercial installations. The flexibility and the advantages of the wireless system (especially the constant power generation) for distributed energy source exploitation are highlighted.

In light of the above, it is concluded that the incorporation of energy harvesters, such as vehicle-applied and vehicle-integrated PV systems, and energy recovery systems (e.g., regenerative braking and thermoelectric Waste Heat Recovery (WHR)) in light-duty and heavy-duty vehicles, constitutes a promising solution for increasing the driving range of AEVs and HEVS, for the fossil fuel consumption reduction of HEVS and conventional vehicles with ICEs, as well as for GHG emission reduction. Particularly, heavy-duty vehicles, such as buses and trucks, facilitate the incorporation of such systems, thanks to their large surfaces (e.g., rooftops) [12,32–36].

All of the above are presented in detail and discussed in this work, in the form of a comprehensive literature review. The remainder of this paper is organized as follows; in Section 2 the framework regarding the environmental footprint of road transportation is set, along with the EU roadmap and guidelines, as we are moving towards greener transportation. Next, in Section 3, a comprehensive literature review is carried out regarding the most significant methods and techniques for the reduction in fuel consumption and GHGs. The aforementioned methods are categorized into on-vehicle (referring to energy harvesting, such as RES incorporation, energy recovery and energy saving methods) and off-vehicle (referring to strategies applicable to EV charging infrastructure) ones. Finally, Section 4 concludes the paper, and a future outlook on further decarbonization of the Transportation Sector is discussed. An outline of this paper, along with the key points that are discussed and analyzed, is illustrated in Figure 2.

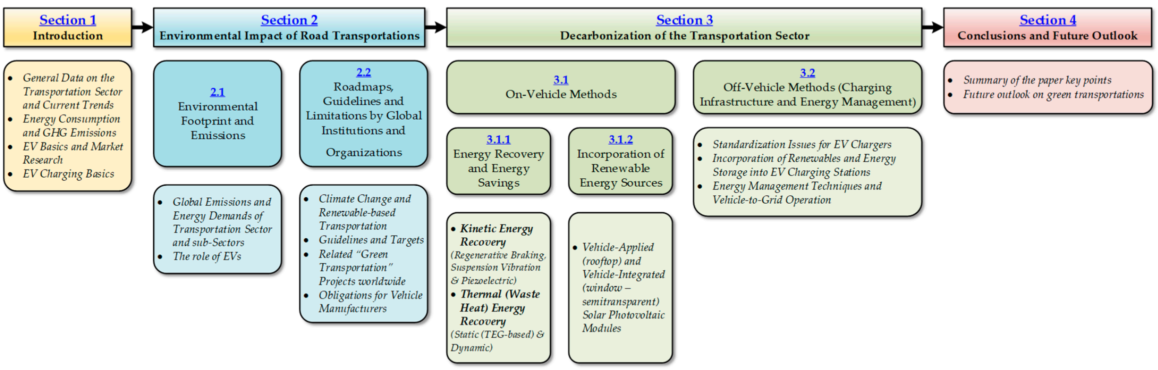

Figure 2. The structure and key points of the paper.

2. Environmental Impact of Road Transportation

2.1. Environmental Footprint and Emissions

According to the recent global data presented by the United States (US) Energy Information Administration (EIA), energy consumption worldwide has increased, with an annual growth rate equal to 2.1%, during the period 1970–2020 [37]. This growth is largely driven by China, the US and India, which, together, accounts for two thirds of global annual growth [38]. In 2018–2019, 59% of the upward trend in energy consumption was heavily affected by the total growth in the use of liquid fossil fuels (i.e., residual fuel oil, diesel, motor gasoline and jet fuel) in the Transportation Sector [37]. Figure 3 presents the total CO_2 emissions of the Transportation Sector worldwide, from 1990 to 2020, by region, according to [37].

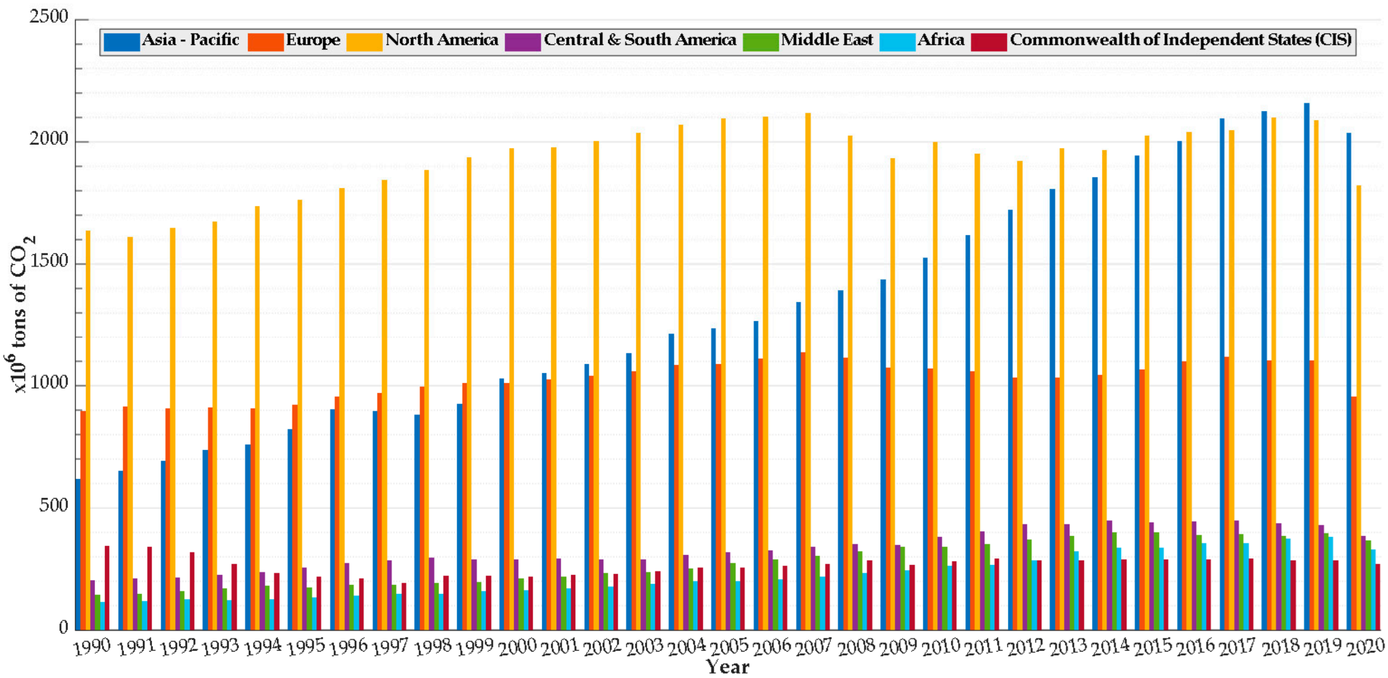

Figure 3. Total CO_2 emissions of the Transportation Sector worldwide, from 1990 to 2020, by region [37].

Specifically, in countries that are not part of the Organization of Economic Cooperation and Development (OECD) the energy demand for the Transportation Sector is estimated to increase by 77%, from 2018 to 2050, in accordance with the 2019 International Energy Outlook (IEO) projections [37]. Due to the fact that China and India have particularly large populations, their energy consumption for both personal and freight travel grows faster compared to many OECD countries. On the other hand, in OECD countries, improvements in vehicle fuel technology (e.g., highly efficient biofuels, renewable fuels, fully synthetic fuels, etc.) hold down the use of fossil fuel in travel demand, resulting in a slight reduction in the total projected energy demands, by roughly 1% from 2018 to 2050. In addition, OECD countries present slower projected economic and population growth and stricter fuel utilization standards than non-OECD countries, leading to a decrease in energy consumption of 3% for passenger travel, for the same period [37]. Figure 4 illustrates the above-mentioned projections, according to IEO 2019 [37]. Additionally, the energy consumption of the Transportation Sector in non-OECD countries has exceeded the respective energy consumption in OECD countries since 2017, whereas by 2050, non-OECD countries will be accountable for almost 65% of global transportation energy demand.

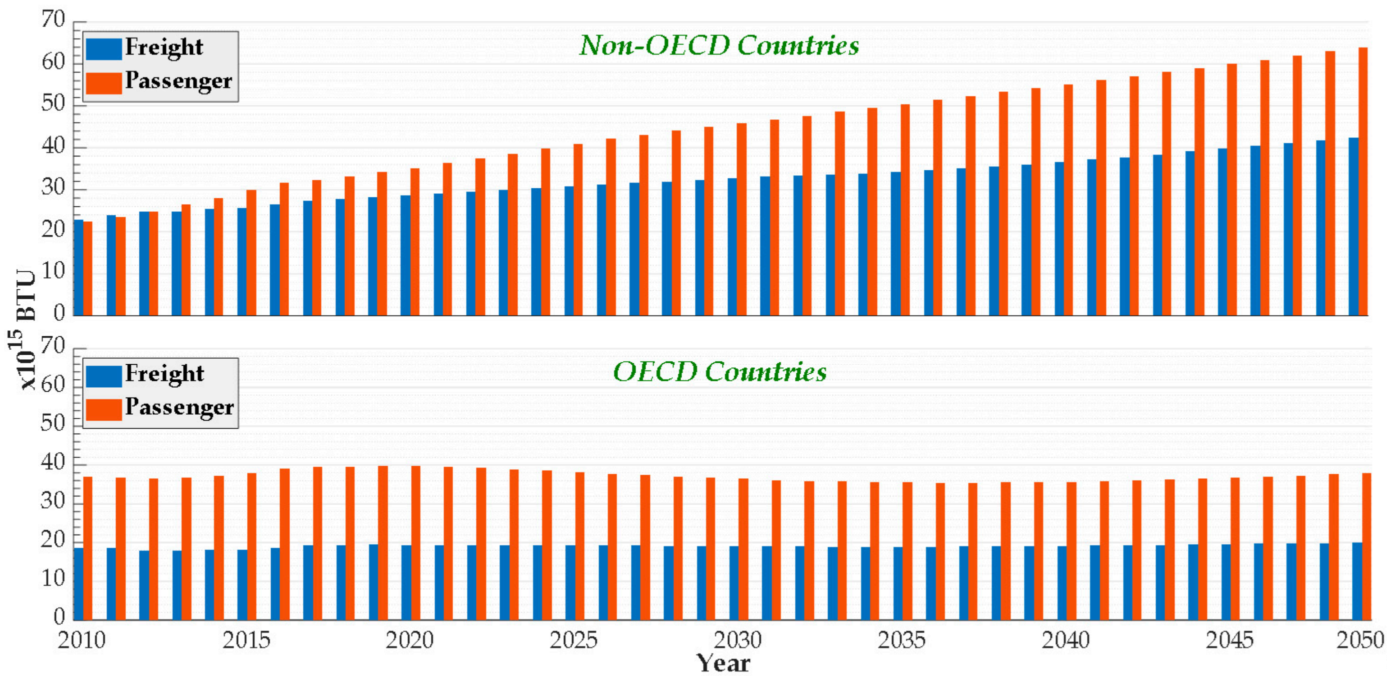

Figure 4. Energy consumption of the Transportation Sector for passenger and freight travel in OECD and non-OECD countries [37].

It is worth noting that the continuously increasing energy consumption of the Transportation Sector is also led by the continuous improvements in transportation means (e.g., more EVs, faster vehicles, advanced infrastructure, etc.) and the ever-reducing lifecycle of products [39]. In parallel, since the Transportation Sector is heavily dependent on petroleum (motor gasoline is its most common form), its negative effects on the environment and climate are evident. Most of the global petroleum is consumed by transportation, causing significant air pollution (high CO_2 emissions), accompanied by negative effects on public health, especially in large urban centers. In 2021, global CO_2 emissions from transportation increased to 7.7 Gt of CO_2 from 7.1 Gt in 2020—corresponding to an increase close to 8%—as the overall mobility demands recovered from the COVID-19 pandemic [7]. The overall CO_2 emissions of the Transportation Sector (i.e., distinguished for each sub-sector) are presented in Figure 5, according to 2021 data [7]. The significant effect of road transportation is evident, as it constitutes the largest fraction of CO_2 emissions, multiple times higher than marine, aviation and rail transportation. Apparently, CO_2 emissions present an upward trend throughout the years 2000–2019, whereas the COVID-19 pandemic's effects are evident for the years 2020 and 2021.

As regards GHGs, they mainly consist of CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases). During the operation of a road vehicle, air and fuel are mixed in a combustion chamber, where combustion occurs. Except for the products of complete combustion, i.e., CO_2, H_2O, excess oxygen and residual nitrogen, which are dominant, there is also a lot of carbon monoxide (CO); unburned hydrocarbons (HCs), such as paraffins, olefins, etc., partially burned hydrocarbons (e.g., aldehydes and ketones); fission products (e.g., acetylene, ethylene, hydrogen and carbon particles); and nitrogen oxides (NO_x), such as nitric oxide (NO), nitrogen dioxide (N_2O) and solid particles. All the aforementioned are further harming the environment [40].

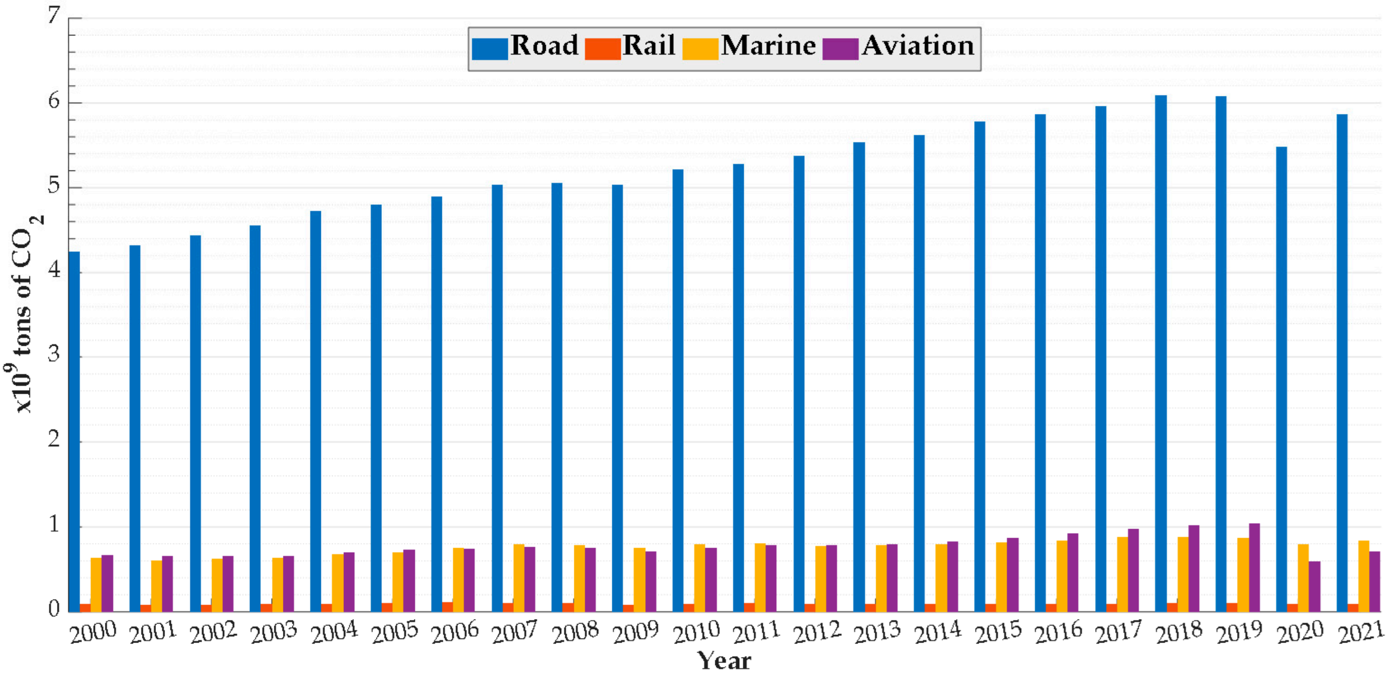

Figure 5. Global CO_2 emissions from transportation, by sub-sector, from 2000 to 2021 [7].

Taking into account the continuous increase in global transportation by around 24% per decade [2], it is presumed that demand for petroleum and other liquid fossil fuels will continuously increase. As a result, the atmospheric concentration of GHGs is aggravating the Greenhouse Effect, leading to major climate change. Global climate change already causes widespread effects on the environment. For instance, glaciers and ice sheets shrink, river and lake ice breaks earlier, plant and animal geographic regions shift, and plants and trees bloom sooner. Many years ago, scientists predicted such global climate changes, as they observed accelerated changing sea levels, ice loss, and longer and more intensive heat waves [41]. In addition, it is certain, to a large extent, that the global temperature will continue to rise for many decades. The “Sixth Assessment Report” by the Intergovernmental Panel on Climate Change (IPCC), published in 2021, found that GHG emissions have already warmed the climate by nearly 1.1 °C since pre-industrial times, whereas the average global temperature rise is expected to exceed 1.5 °C within the next decade, affecting all regions on Earth [42]. However, as the severity of the negative effects caused by climate change depends strongly on the amount of GHGs, these effects can be mitigated by reducing the use of fossil fuels [43].

It is worth noting that, according to the International Energy Agency (IEA), decarbonizing transportation in a Near-Zero Emission (NZE) scenario depends primarily on two factors. The first one is the so-called “switching to electricity”, implemented particularly by the use of EVs and hydrogen Fuel Cell EVs (FCEVs). The second one is based on the combination of both EVs and modern low-emission fuels, such as biofuels, hydrogen and hydrogen-based fuels. In the NZE scenario, the share of oil products in road transportation demand decreases to 75% by 2030, with electricity accounting for 10%, biofuels for more than 10%, and hydrogen, hydrogen-based fuels and natural gas for the rest. The actual share of RES-based electricity and biofuels in 2009 and 2019 was 2.4% (i.e., 0.2% RES electricity and 2.2% biofuels) and 3.7% (i.e., 0.4% RES electricity and 3.3% biofuels), respectively [2]. Even though global EV sales tripled between 2019 and 2021, the total CO_2 emissions in 2021 were 5.9 Gt, with the share of electricity in road transportation demand being less than 1% [7]. Therefore, in order for the Transportation Sector to comply with the Paris Agreement’s goal of limiting global warming below 2 °C, the overall global GHG emissions from road vehicles in 2050 need to be substantially lower than those of today [44]. Additionally, it is of paramount importance for policymakers to understand which powertrain and fuel technologies are most capable of mitigating the environmental footprint of transportation, by saving fuel and improving the vehicle manufacturing process, at the same time. For example, for light-duty vehicles, which account for the majority of transportation emissions, specific targets have been set. Car manufacturers are obliged to ensure that their new models emit less than 95 gr of CO_2/km, during the period of 2020–2024, whereas for vans, the specific targets are 147 gr of CO_2/km, for the same period of time [45].

In an attempt to further decarbonize road vehicles, several of the most relevant modern powertrains, fuel types and power sources have been adopted. According to a recent study, elaborated by the International Council on Clean Transportation (ICCT), only Battery EVs (BEVs) and FCEVs contribute to the further decarbonization of passenger cars, with BEVs producing, on average, lower life-cycle emissions by 66–69% in Europe, 60–68% in the US, 37–45% in China and 19–34% in India, compared to gasoline cars of the same size [44]. The continuous electrification of transportation until 2030, in conjunction with the decarbonization of electricity generation and medium-size BEV registrations, are the main factors that are expected to decrease the gap in EV sales compared to conventional gasoline cars. By this time, pure RES-based energy will supply the entire BEV fleet life-cycle, whereas their GHG emissions will be 81% lower than the respective ones of existing gasoline cars [44]. On the other hand, the life-cycle emissions of FCEVs are about 26–40% less than an average gasoline car; apparently, this represents poorer environmental performance than BEVs. However, in cases whereby FCEVs utilize hydrogen that is produced purely from RES electricity, the 76–80% reduction in GHGs—compared to gasoline cars—becomes 76–80%, as well [44].

Even though the registration of new ICE vehicles should be phased out during the 2030–2035 time period, the mass transition to BEVs (supplied exclusively by renewable electricity) and FCEVs (fueled exclusively by green hydrogen), which are the only two qualified technology roadmaps, is not expected to be achieved in a short period. Thus, further hybridization and biofuels should be utilized, in order to reduce the environmental impact in the meantime. Neither HEVs nor plug-in HEVs (PHEVs) seem to provide a drastic reduction in GHGs, which is imperative in the long term. Although HEVs are capable of reducing life-cycle GHGs by approximately 20% compared to conventional gasoline cars, their environmental performance is far from that of medium-sized PHEVs; the latter achieve a GHGs reduction of 42–46% in the US, 25–27% in Europe and 6–12% in China [44]. Finally, the utilization of low-carbon biofuels contributes to a significant reduction in the GHG emissions of gasoline cars; however, the production costs still remain high. According to [44], the expected future changes in biofuel blends, driven by current policies, lead to a maximum reduction of 9% in GHG emissions.

2.2. Roadmaps, Guidelines and Limitations by Global Institutions and Organizations

Considering the above discussion, it is presumed that there is a need for measures, guidelines and limitations to be set by international organizations and institutions regarding climate change, GHG emissions and RES-based transportation. It is remarkable that only 28 countries worldwide have set targets for the use of RES in transportation, and only 11 countries have set bans on sales of ICE-based vehicles. Despite the delayed reaction of global society, the trend is currently changing. Specifically, 31% of climate mitigation finance is allocated to low-carbon transportation. Furthermore, 270 cities have already established low-emission zones, whereas 20 cities have adopted pass-bans and restrictions for vehicles fueled by certain fossil fuels [2]. For instance, an important initiative towards the carbon neutrality goal has taken place in the city of Petaluma, California, where the construction of new gas stations is restricted [2].

Although the electrification of road transportation is necessary, the targets that have been set have not been achieved, yet. It is imperative to significantly reduce GHGs that are emitted during the whole life-cycle of a vehicle, whether conventional or electric. Even for EVs, it is important to ensure that their charging demands are not based on fossil fuel energy. In this section, an overview of relevant guidelines, limitations and roadmaps, provided by global institutions, agencies and organizations, is provided.

Moving towards greener transportation, the EU and several global organizations have set some strict targets and limitations for the Transportation Sector regarding GHG reduction. Additionally, according to [2], a large number of transportation-related commitments were set during the 26th UN Climate Change Conference of the Parties (COP26) that was held in Glasgow in 2021, which focus on zero-emission vehicles and charging infrastructure. During the COP26, 30 countries and six major vehicle manufacturers agreed that all new car and van sales should be zero-emission by 2040 globally, and by 2035 in leading markets (e.g., the EU). Moreover, during the aforementioned conference, the "COP26 Declaration on Accelerating the Transition to 100% zero Emission Cars and Vans" was established, which brought together a great number of factors that affect transportation deployment, in order to cooperate (i.e., 35 countries, 43 cities and states, six major car manufacturers, 28 fleet owners, financial institutions and investors), and thus, achieve this common goal. Specifically, General Motors, Jaguar, Fiat, Volvo, Audi, Ford and VW committed to 100% zero emission vehicle production by 2035 [45]. Furthermore, it is worth noting that in 2021, 20% of the global car market committed to phasing out conventional fuel vehicles (i.e., a 15% increase, compared to the respective 2019 percentage). Additionally, more than 40 countries, accounting for over 70% of the global Gross Domestic Product (GDP), agreed on a breakthrough agenda in order to achieve a sustainable future. Regarding road transportation, these countries agreed to work together in order to establish zero-emission vehicles [46].

However, there are already obligations for car manufacturers to reduce the environmental footprint of their vehicles. According to [47], there are specific targets for every vehicle category. Since 2015, car manufacturers have had the obligation to ensure that their new cars will not emit more than an average of 130 gr CO_2/km, and 95 gr CO_2/km by 2021. These constitute notable reductions from the respective targets of 2007 and 2012, when the reference values were 160 gr CO_2/km and 132.2 gr CO_2/km, respectively. For van-type vehicles, these targets are different. Specifically, the target by 2017 was to not emit more than an average of 175 gr CO_2/km, whereas for 2020, the respective target was 147 gr CO_2/km. The respective goals for the years 2007 and 2012 were 203 gr CO_2/km and 180.2g CO_2/km, respectively. Additionally, according to [47], a large contributor to the EU's CO_2 emissions is heavy-duty vehicles. Specifically, their emissions account for 25% of road transportation emissions and 6% of EU GHGs. Within the years 1990 to 2010, their emissions increased by 36%, whereas a significant increase of 9% is expected for the years 2010 to 2030. In light of this, according to [48], Japan, the US and Canada were the first countries to take measures to reduce CO_2 emissions caused by heavy-duty vehicles. In parallel, in April 2010, the European Commission announced that it would propose a strategy, with a view to reducing heavy-duty vehicle fuel consumption and CO_2 emissions. Moreover, in 2013, the EU initiative "Clean Power for Transport: A European alternative fuels strategy" launched, aiming to increase alternatives to conventional fossil fuels for heavy-duty vehicles [49]. Additionally, the EU uses funds to support the targets that have been set for the aforementioned vehicle category. In parallel, the Zero Emission Urban Bus System (ZeEUS) is a program that is co-funded by the EU, and began in 2013, in order to achieve GHG reduction in Urban Europe [50]. Specifically, ZeEUS focuses on plug-in hybrid buses, battery-powered electric buses and battery-powered trolleybuses. Within the framework of ZeEUS, several innovative solutions for e-bus technologies and charging infrastructure have been investigated, across various European countries, in order to evaluate their economic, environmental and social viability. Furthermore, another important European-funded research program is called FREVUE (Freight Electric Vehicles in Urban Europe) [51]. The main goal of this program is to reduce or even eliminate CO_2 emissions in city centers. Hence, the FREVUE project aims to introduce electric freight vehicles into urban area logistics [52]. In more detail, more than 80 electric freight vehicles were used and 75 charging points were installed in European cities. Additionally, various pre-booking systems for electric freight vehicles, as well as operational incentives, were tested.

Over the last decade, more and more initiatives and reports that focus on transportation's environmental footprint have been established. According to [53], in 2018, with the European Commission communication entitled "A clean Planet for all—a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy", the transformation of the Transportation Sector (in order to achieve the Paris Agreement) was targeted. Furthermore, within the past few years, the EU has funded a number of research programs, such as the "European Green Cars Initiative PPP Multi-annual roadmap and long-term strategy" and the "HORIZON 2020—WORK PROGRAMME 2014–2015, Smart, green and integrated transport" [54,55]. Specifically, the first one [54] constitutes a Public–Private Partnership, launched by the European Recovery Plan. Its goals are related to energy generation, storage and distribution, highly energy efficient vehicles, the incorporation of Information and Communications Technology (ICT) solutions and the management of mobility and logistics. In addition, the second one [55] focuses on four axes, i.e., (1) resource-efficient transportation that respects the environment; (2) better mobility, less congestion, more safety and security; (3) global leadership for the European transportation industry; and (4) socio-economic and behavioral research and forward-looking activities for policy making.

In parallel, according to [47], and taking into consideration the aforementioned actions aimed at GHG emission reductions, IEA expects that an overall CO_2 reduction from passenger cars of 70% will be achieved by 2030. This expectation is also based on the assumption that by 2030, the mix of passenger cars will include only 30% conventional cars. In addition, in [47], milestones for 2030 and 2050 regarding the EU are presented. Specifically, it is expected that EVs should obtain 60% of the market share of the overall number of vehicles by 2030. Moreover, further targets have been set for the currently operating models to be supported by the available storage systems and infrastructure. The second milestone about the deployment of transportation electrification in the EU should is set to be achieved by 2050. Specifically, by this year, the target is to obtain 100% CO_2-free road transportation. By then, the largest part of road transportation will be electric, and the rest will be based on other fuels. Last, but not least, by 2050, EVs should be greatly integrated into mobility systems, and therefore, technologies such as big data, artificial intelligence (AI) and quantum computing will be used to optimize the operations, in order to achieve these targets.

Finally, a great initiative of the EU is the "Green Deal", which aims to accelerate the reduction in GHG emissions and slow down the average global temperature increase. According to [56], in the context of the "Green Deal", the EU aims to achieve a 90% reduction in GHGs in transportation by 2050. Furthermore, another important milestone constitutes the achievement of 30 million zero-emission cars and 80 thousand zero-emission trucks by 2030. Moreover, any scheduled group travel within the EU, below 500 km, should be carbon-neutral. This will also be supported by the wider use of rails. In particular, by 2030, traffic on high-speed rails and rail freight traffic are expected to double. Last, but not least, it is worth highlighting the 2022 EU Parliament decision to phase out internal combustion engines in new passenger cars and light commercial vehicles from 2035, within the framework of the EU climate package "Fit for 55". This is to ensure that by 2050, the Transportation Sector can become carbon-neutral [57,58].

To conclude, GHG emissions from road transportation have presented an uptrend during the last few decades. In this context, both the EU and several other international organizations aim to achieve a sustainable, carbon-neutral future with significantly fewer emissions. This will be achieved and accelerated by establishing initiatives, incentives and research projects, focusing on GHG reduction in road transportation.

3. Decarbonization of the Transportation Sector

3.1. On-Vehicle Methods

3.1.1. Energy Recovery and Energy Savings

As mentioned above, transportation accounts for 30% of the global total delivered energy, affecting countries' economies and social development [59]. Road vehicles and railways are widely used for transporting freight or passengers from one location to another. However, a large fraction of the energy used to power ICEs is wasted as heat through the exhaust pipes, resulting in an increase in fuel consumption and GHG emissions. For example, for a typical gasoline car, the overall energy losses are estimated to be close to 78% of the fuel energy, due to exhaust gases, cooling and mechanical losses caused by friction in the engine and transmission, using only 21% of the total power to supply the wheels [60]. Even BEVs and PHEVs suffer from energy losses similar to those described above, whilst the total energy used for driving is 77–82%, according to the US Environmental Protection Agency [61], making them significantly more efficient than conventional cars. In an attempt to achieve deep decarbonization, many researchers have recently presented various solutions and new technologies to achieving a greener and more efficient way to move passengers and freight. Therefore, energy harvesting technologies based on modern power electronics concepts are applied to reduce vehicles' energy consumption and GHG emissions, as the transition to BEVs and FCEVs gradually takes place. Energy harvesting technologies can capture unused or wasted energy and convert it to useful energy. With increasingly efficient new ways of harvesting wasted or unused energy, road transportation will be able to reduce its environmental footprint.

Kinetic energy, i.e., the energy recovered from electric motors during a braking event, constitutes huge energy saving potential. When a vehicle is decelerating or accelerating, it creates vibrations in all directions. Therefore, energy can be recovered from suspension vibrations. In a conventional vehicle braking system, where 1/3 or even 1/2 of the engine energy is dissipated in the form of heat [62], regenerative braking can be a valuable solution to improving fuel economy, estimated at around 15% [60]. Furthermore, regenerative braking can be applied to PHEVs, HEVs, BEVs and FCEVs, and generally to vehicles powered by an electric motor. When a vehicle decelerates, the electric motor operates as a generator, feeding energy into the energy storage units (batteries, supercapacitors or hybrid configurations). In [62], the experimental results indicate that under specific and predetermined driving cycles, the contribution ratios of regenerative braking to energy efficiency improvement and to driving range extension were up to 11.18% and 12.58%, respectively. Additionally, on railways, energy savings from regenerative braking range from 10% to 45%.

According to [63], in the electromechanical system of the 8000-series Athens trolleybuses (data provided by OSY S.A.), an effort was made to estimate energy savings after the installation of a regenerative braking system. The results of this study obtained energy savings of up to 24% of the daily energy consumption. However, regenerative braking cannot meet the overall braking requirements, but only a part of the entire braking system demand. As a result, friction regenerative braking systems can be implemented to harvest a portion of the remaining wasted energy and effectively apply this energy to the vehicle power distribution system. Electromagnetic, flywheel and hydraulic systems are designed for this purpose, and they have to cooperate with the main regenerative braking systems, under a synergetic control scheme [60].

An electromagnetic braking energy recovery system usually consists of a transmission mechanism, a clutch or switch and a generator. During the braking period, the clutch transfers the power from the wheel to the generator through the transmission mechanism. As for the flywheel system, high-strength carbon fiber composites (greatly increasing the kinetic energy reserve per unit mass) and magnetic levitation technologies (minimizing the friction losses of flywheel rotors) are placed inside a vacuum chamber (reducing aerodynamic losses) to successfully store high amounts of energy, with negligible power losses and extremely fast responses to instantaneous high power demand, making flywheel energy storage a suitable option for braking energy recovery systems. Finally, hydraulic systems are widely used in various transmission systems to improve system performance, transmitting energy through fluids under pressure [60].

On the other hand, suspension vibration energy recovery systems are able to recover energy from 100 W up to 400 W with respect to the vibration intensity, supplying power to the vehicle's electrical equipment, improving its energy efficiency, and thus, increasing its range. The commercially available energy shock absorbers are divided into three categories: linear motor-type shock absorbers (able to convert the kinetic energy of linear motion into electric energy, based on the principle of electromagnetic induction), hydraulic shock absorbers (the reciprocating motion of pistons in the cylinder is converted by hydraulic shock absorbers into rotation of the hydraulic motors and generators) and mechanical-type shock absorbers (which use various mechanical mechanisms to amplify input excitation, and then, transform the linear motion of dampers into the rotation of generators); each has both advantages and disadvantages regarding power generation, cost, efficiency, size and design complexity [60]. For instance, linear motor shock absorbers feature high controllability, but they require accurate system design, which causes higher costs, whereas the constant change in the motor motion direction causes losses in inertial power, and thus, it reduces the energy conversion efficiency.

Except for regenerative braking systems, which hold the highest share of energy recovery systems, the second-largest fraction of energy harvesters corresponds to the WHR systems that are now based on thermoelectric generators (TEGs). TEGs consist of several N-type and P-type semiconductor materials, which are connected electrically in series and thermally in parallel. When a temperature difference exists among the TEG sides (i.e., hot and cold sides), an electric voltage is generated thanks to the Seebeck effect [64]. Thus, TEGs are capable of directly converting thermal energy to electrical energy, and they have been successfully adopted by the automotive industry (where applications with significant temperature differences exist) to recover waste heat energy. Their efficiency typically ranges from 5% to 8% [65]. What is more, heat pipes are considered to be a great addition to TEG systems, in order to reduce the thermal resistance between the two surfaces [65], and thus, to significantly improve the overall efficiency. In heavy-duty vehicles, such as city buses, the amount of energy that is converted into heat (thermal loses) is close to 30% [66]. Therefore, the use of TEG-based WHR systems in modern transportation applications is necessary, so as to maximize heat recovery. TEGs are designed to utilize waste heat from the exhaust pipe (450–600 °C) and the engine coolant loop (100 °C), without compromising the safe operation of the vehicle. To obtain the best performance, different thermoelectric materials are selected to match different temperature ranges [67]. Recent studies (i.e., [68,69]) reach the conclusion that for heavy-duty vehicles, the savings are close to 5–6 kW (for maximum operating temperatures of 500–650 °C), whilst the fuel savings can rise up to 8.55%. Moreover, large multinational car companies such as BMW [70], Ford [66], Renault [66] and Honda [71] have demonstrated their interest in exhaust WHR by developing systems that make use of TEGs with all of their designs, sharing many parts. Typically, TEGs are placed on the exhaust pipe surface and are cooled with an engine coolant or any kind of cooling system that utilizes air or liquid. For example, Honda designed a simple liquid cooling system, comprising 32 TEG modules (30 mm $\times$ 30 mm) that are placed on the top and bottom surfaces of a thin, flat, rectangular box (exhaust gases pass through the box), with a maximum power output of 500 W. The model was estimated to reduce fuel by almost 3%. This power can be used to offset the auxiliary load demands of the engine (cooling radiator fan, lights, etc.), leading to lower fuel consumption [64]. Generally, those WHR systems that have been designed by the aforementioned car manufacturers will be able to produce power from 400 W up to roughly 1 kW, depending on the number of TEG modules, as well as their efficiency.

As regards TEG energy harvesting technology, significant growth has been achieved over the last few years, driven by the developments in semiconductor materials. In order to enhance TEG energy efficiency, Maximum Power Point Tracking (MPPT) algorithms are employed. Simulations that utilize these algorithms present performance enhancement of up to 9% with a 4 × 3 fixed array for a TEG module mounted onto a vehicle radiator, despite the dynamic variations in coolant temperature at each TEG module [72]. The proposed method is estimated to achieve 34% performance enhancement with a 10 × 10 fixed array TEG system in a real vehicle radiator.

With the rapid development of power electronics and the improvements in material science, several alternative methods for harvesting energy and reducing energy consumption have been developed. Starting with piezoelectric energy harvesting systems, they were first proposed for highway applications (e.g., the passage of vehicles through tollgates, speedbumps or even pavements); they initially presented very low energy generation capability; however, thanks to the advances in piezoelectric materials, piezoelectric harvesters are now a valuable solution with several advantages, such as system simplicity, a wide frequency range, high power density and good scalability [73]. As the piezoelectric industry evolves and develops, public transportation seems to be an appealing application for this technology. Specifically, with the daily passage of a large number of passengers, as well as the available space (e.g., bus floors) for the installation of such technologies, a new and promising field for the mass integration of piezoelectric generators into public city buses is introduced [74]. Moreover, in [73] various experimental suspension system models are studied, where piezoelectric harvesters are utilized in various configurations (i.e., parallel with the suspension, on the suspension wheel, embedded in the wheels, at the inner surface or at the center of the tire, at the shock absorber, etc.). In this study, most of the experimental suspension system models were built for the quarter car model (i.e., the simplest representation of a vehicle in dynamic analysis, consisting of the most essential degrees of freedom that describe its movement), by using two parallel plates connected with springs and dampers. Regardless, for the technique used in energy harvesting from a vehicle suspension, the outcome is still limited, ranging from about 0.001 mW to around 3.9 mW. In conclusion, various improved methods could be suggested to maximize the piezoelectric energy yield (a different piezoelectric stack arrangement that could amplify the power production), as well as innovative and more efficient piezoelectric elements with improved material characteristics for converting vibrations (of the car suspension) into useful electrical power. On the other hand, the incorporation of modern, intelligent power converters into conventional, inefficient systems leads to a notable reduction in energy consumption. In accordance with [75], an innovative energy recovery unit for the LED lighting system of heavy-duty vehicles was implemented, to reduce energy consumption. This technology improves the existing truck's lighting system by eliminating the so-far inevitable power consumption by conventional incandescent and fluorescent lamps applied in the majority of vehicles, by replacing them with an LED lighting system. The significant advantages of LED technology force the majority of heavy-duty vehicles, such as buses, trucks and lorries, to incorporate it into their lighting systems. However, due to the fact that most of the vehicles' Central Control Units (CCUs) cannot recognize the LED's extremely low power consumption in normal operation, the lighting system is driven to a faulty condition. To solve this problem, a power converter was developed in [75], in order to draw the proper amount of power from vehicle batteries. This unit is capable of virtually increasing the lighting system power consumption without actually consuming this amount of energy, and thus, the CCU operates normally, without noticing any difference. Additionally, when the CCU recognizes an energy surplus, this amount returns back to the batteries. The annual energy savings in lighting systems with the aid of the aforementioned product are close to 70% [75].

3.1.2. Incorporation of Renewable Energy Sources

Within the last few years, energy recovery and energy saving systems have been studied in depth by both researchers and the car manufacturing industry. In the above sub-section it was shown that many recently published scientific works focus on energy recovery and energy saving systems. Moreover, the continuously growing energy demands of the Transportation Sector have increased efforts towards the incorporation of RES, as well. Indeed, Vehicle-Integrated Photovoltaic (VIPV) products are already commercially available, e.g., [76–78]. Specifically, in this sub-section, an overview of the research carried out in this field is presented. From a comprehensive literature review, it is determined that the renewable energy that is most commonly adopted is solar PV energy. In addition, according to [74,79], it is evident that PVs are utilized in EVs, HEVs and conventional cars. In each case, the produced energy supports either the vehicle electrical microgrid or Vehicle-to-Grid (V2G) operation, which is described in more detail in the next Section. Unfortunately, the incorporation of other types of RES in road vehicles has not yet been studied in depth.

The idea of RES integration into vehicles is not new [80–83]. According to [84], in 1985, the first solar race took place. In this race, cars were powered only by solar energy. After this race, the great potential of solar-powered vehicles was pointed out. The potential of PV integration in modern vehicles was also highlighted in the same work. In more detail, it is estimated that with a typical vehicle roof of 1.7 m^2 to 2 m^2, equipped with solar cells, a solar-powered distance ranging from 1900 km/year to 3400 km/year can be achieved. This distance corresponds to 13–23% of the average annual driving range of cars in Germany (15,000 km). It is worth noting that in this work, only the roof area was considered as an available surface for PV installation. Given that modern PV cells have an efficiency of 22%, and with the expansion of their installation in windows and car hoods, a yearly driving range of roughly 15,000 km with solar energy may be achievable under advantageous conditions [84].

Moreover, in [74], a technical solution for city buses is proposed. This solution includes rooftop- and window-integrated PV modules. According to the results of this work (using actual data from the city of Athens, Greece), the minimum monthly energy production from bus-applied and bus-integrated PVs is around 40 $kWh_{e/}1$ kWp for rooftop BIPVs, for the season from November to February. On the other hand, for the season from April to September, the proposed system produces 100 $kWh_{e/}1$ kWp for rooftop BIPVs on a monthly basis. It is noticed that although the energy yield is 23% below the average PV production in Greece, the energy produced on an annual basis is capable of meeting the electric load of the bus. In addition, in [85], a campaign on six trucks (of 40 t) took place. Specifically, PV panels were installed on the trucks' rooftops. The trucks operated in central EU and north-eastern US, for a time period of 14 months. The conclusions of this work indicate that the energy yield corresponded to 1513 lt and 2113 lt of fossil fuels per year for trucks 1 and 4, respectively. Furthermore, according to [86], PV modules of 100 Wp could be installed on the tops of motor-homes and buses, in order to charge their lead-acid batteries. In parallel, in [87], the potential of VIPVs in commercial trucks and vans was estimated, too. Five different vehicle categories were investigated (i.e., a parcel delivery van; a rural delivery truck; a long haul truck; a trailer; and a trailer with a battery) in the European cities of Stockholm, Freiburg and Seville, and five operational scenarios were analyzed. The results of this work indicated that the proposed system for the parcel delivery vans can cover from 35% to 60% of the overall energy needs, which corresponds to 6,637 km/year to 11,450 km/year. However, for the smaller vehicles (such as the trailer), only a small amount of energy, such as 0.9% to 1.6%, can be covered by solar energy. In terms of financial feasibility, the payback period for the considered scenarios ranges between 3.4 years and 7 years, considering a PV module cost of EUR 1/Wp.

Additionally, in several works, such as [88–92], a combination of solar power and fuel cells is proposed and studied. Particularly, in [92], a PV-powered high-pressure electrolyzer integrated with a fuel cell system is incorporated into an EV and tested. It is concluded that fast irradiance variations do not affect the electrolyzer system response. In [89], a microgrid comprising 10 houses and five FCEVs is investigated. Specifically, simulations are carried out, in the context of the "Car as Power Plant" project in the Green Village in the Netherlands. The main aim of this work is to evaluate the potential of utilizing FCEVs in V2G operation. Various scenarios are examined, whereas the worst-case scenario corresponds to simultaneous peak load demands. Finally, it is estimated that when utilizing FCEVs for V2G operation, the annual electricity grid demands can be reduced by up to 71%.

Last, but not least, the idea of RES installation (especially PVs) on a vehicle surface is constantly gaining interest compared to previous years, when it was considered a technological immature concept. However, the Return-on-Investment (ROI) constitutes a barrier to the greater adoption of this technology, and the weight of the PV modules affects the vehicle design and operation. Therefore, lightweight and durable PVs should be adopted. Fiber-Reinforced Composite (FRC) PV modules comply with both the above-mentioned criteria. Additionally, considering that FRC PVs are manufactured by encapsulating silicon solar cells into a transparent composite material, it is presumed that they can be curved and adapted into various surface finishes [93]. In [86,94], an overview of enhanced lightweight PV modules for VIPV applications is presented. Nevertheless, the imperative need for greener road transportation has led to the investigation and utilization of off-vehicle methods, as well, in order to minimize the environmental footprint.

3.2. Off-Vehicle Methods (Charging Infrastructure and Energy Management Strategies)

According to [95], the largest amount of energy consumption during the life-cycle of an EV corresponds to its battery charging. Specifically, the energy fraction that is used for the charging operation is 71.50% of the overall energy that an EV consumes throughout its life-cycle. The share of battery production is also high, corresponding to 16.7%. In addition, the energy used for the production of other parts and components, transportation and disposal comprises the remaining 11.80% of the energy that is used during an EV's life-cycle. Furthermore, nowadays, the mass adoption of EVs and HEVs has a notable impact on the electricity grid, due to the continuously increasing charging demands. According to [19], the global EV fleet in 2021 consumed about 55 TWh of electricity, which is similar to the overall electricity demands in Greece [96]. The use of energy management techniques and the incorporation of RES in charging infrastructures are considered imperative prospects. In parallel, another option is to use incentives for EV users, such as time-of-use tariff, in order to encourage them to charge their vehicles during off-peak hours or when there is extra energy from RES [16]. This tariff will push users to charge their EV efficiently and in an environmentally friendly manner during the hours when RES-generated power is high. The aforementioned technique (i.e., the time-of-use tariff) is one of the three main types of smart charging. The others are unidirectional managed charging (i.e., a control scheme for charging time, rate and duration, based on prices and power system needs) and V2G operation [16].

According to the recent scientific literature, there are several works, such as [97] and [98], that focus on energy management schemes for an RES-based microgrid, incorporating EV charging infrastructure. The energy management scheme presented in [97] is based on a machine learning model that predicts the charging demand of EVs. The results of this work prove that the proposed prediction model can achieve a 2.5% reduction in microgrid operating costs. On the other hand, [98] investigates an energy management system for a microgrid, which comprises a multiport EV charger. The charger can be powered by a PV system, an ESS and a regenerating braking system of a railway. The proposed multiport charger provides 12 kW of power by adapting the DC level 1 charging standard (200 V–450 V, 80 A, up to 36 kW), accommodating the type 1 SAEJ1772 connector, a standard connector for EV charging established by the Society of Automotive Engineers (SAE). The proposed system is capable of maintaining the DC bus voltage within certain limits, even in grid overloading, through a delay in or the temporary interruption of EV charging. Furthermore, to cover the overall microgrid power demands, either the ESS or the V2G technology (in cases whereby an inverter with V2G capability is utilized) are adopted.

It is worth noting that in the majority of cases investigated in [95,99–101], it is concluded that the main target is to supply the EV charging stations with RES-generated power, i.e., PV and wind energy. Particularly, in [99], the Markov chain stochastic model is used, in order to analyze the PV utilization of an EV charging station, because of their intermittent nature. The PV system size is optimized, in order to fully meet various energy demand scenarios. Hence, it is concluded that when the utilization of solar energy is maximized, minimum energy is supplied by the utility grid. However, a major problem to overcome when greater renewable energy amounts are generated is the need for larger ESS capacity. Nowadays, significant research is carried out on innovative technologies for electrochemical ESSs, whereas several types of lead-acid and lithium ion (Li-ion) battery have recently been reported in the scientific literature. Specifically, in [102–105], several ESSs based on lead-acid batteries are analyzed, whereas in [106–109], ESSs based on Li-ion technology are studied. The aforementioned ESS technologies and energy management systems promote the new concepts of V2G and Vehicle-to-Vehicle (V2V), assisting in the minimization of the environmental footprint of road transportation, as well as utility grid sustainability.

Therefore, the utility grid perceives EVs as mobile storage units, supplied by RES, which are capable of supplying energy back to the grid during peak-load hours [16,110–113]. Power transfer during V2G and V2V operation is accomplished with the aid of a bidirectional power converter with an effective control strategy. For instance, in [95], a smart DC fast EV charging station, which is powered by PVs and incorporates V2G operation, is studied. The aforementioned concept constitutes a "PV-based grid-connected EV", which is capable of providing support and compensation for the intermittent nature of RES. In parallel, in [101], an RES-based DC microgrid (i.e., wind and solar) incorporating a residential EV charging station is examined. Both grid-tied and islanded operation are studied, whereas the charging station can deliver 30 kWh of clean energy with the aid of a mini-pumped hydro storage hydro unit. Furthermore, the study of an RES-based grid-connected EV charging station in Bangladesh is presented in [114]. The aforementioned system is simulated via the HOMER software platform with real components (i.e., a 4.8 kW PV system and a 10 kW wind turbine), and it can supply a 105 kWh/day load, which corresponds to the charging of 12 mini EVs. The authors state that the specific system is capable of reducing annual CO_2 emissions by approximately 20 t.

As regards the PHEV category, according to [115], by charging multiple PHEVs multiple times a day, about a 71% and 66% improvement in fuel economy for PHEV-20-type (i.e., 20 miles all-electric range) and PHEV-40 (40 miles all-electric range)-type vehicles can be achieved, respectively. Moreover, the works in [115,116] present the design of two RES-based EV charging stations in workplace areas that are implemented in the US and in the Netherlands, respectively. Specifically, in [115], an outdoor parking infrastructure with PVs installed on its rooftop is suggested. By using such parking structures, CO_2 emissions can be reduced by 90%, compared to charging PHEVs without using solar energy. Another significant outcome of this work is that in cases whereby an EV is charged at the workplace by a purely solar-powered charger, 0.6 t of CO_2 per year can be saved, which corresponds to 55% savings, compared to charging using conventional utility grid power during the night (i.e., low-demand hours). In addition, two control algorithms are employed that consider the charging time and the number of EVs that enter and exit the charging garage. In parallel, in [116], two different scenarios are studied, which both use solar energy (i.e., 10 kWp PV arrays, located either on the rooftops of buildings or on the rooftops of parking slots, as in [117–120]). The first and second scenarios correspond to the charging of the EVs for 7 days/week and 5 days/week, respectively. In the second scenario, due to the increased amount of PV-generated energy that is fed back to the grid, there are fewer transactions with the utility grid. Another highlight of [116] is that at workplaces, there is no need for fast chargers to be installed because of the long parking times. Last, but not least, in order to provide green energy to EVs, it is imperative to utilize RES in their charging infrastructure; in addition to PVs, there are two more green technologies that can be employed in EV charging stations, i.e., biomass and hydrogen fuel cells. As for biomass, an important advantage is that the feedstock can be stored, so as to be used when there is demand [121,122]. However, biomass feedstock comes with negative consequences for the environment, due to its GHG emissions. Thus, it is recommended that it is avoided in urban areas. Finally, according to the recent scientific literature, some EV charging stations that incorporate hydrogen fuel cell technology have been reported, and they have been proven to be cost-effective [123,124]. Finally, in Figure 6 an RES-based, fast EV charging station is presented. Specifically, the station constitutes a DC microgrid, which includes a wind generator, a PV system, an ESS and interconnection with the utility grid. According to the above-mentioned works, the charging process is based mainly on RES and ESS, utilizing the utility grid only is cases whereby the local units/reserves cannot meet the energy demand.

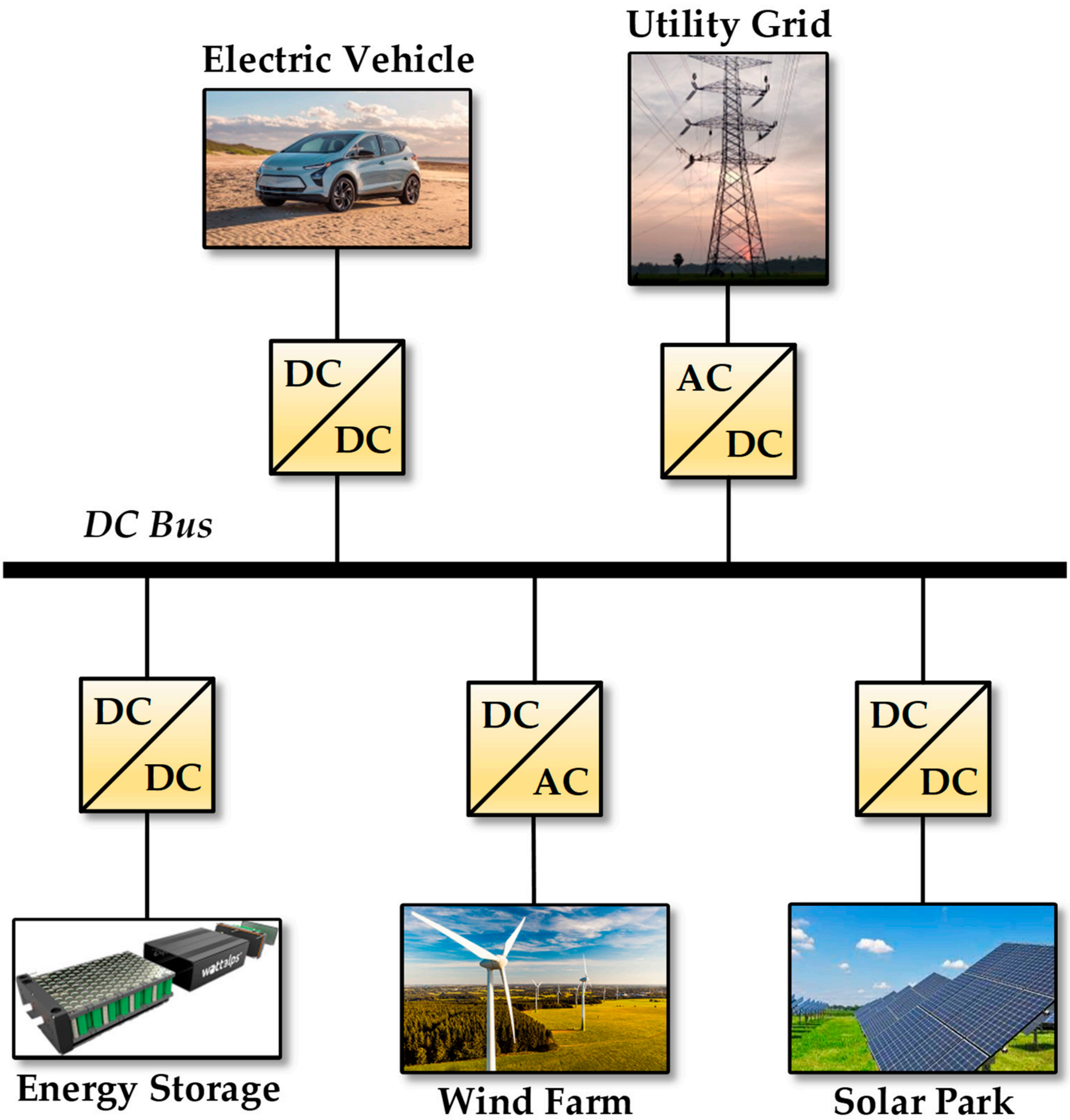

Figure 6. Generalized block diagram of an RES-based EV charging station.

To conclude, it is apparent that EV charging infrastructure constitutes a crucial parameter in the mass adoption of e-mobility. Until now, EV charging stations have mostly been based on the utility grid, and thus, on fossil fuels, which definitely causes environmental problems, and so it is not considered a sustainable solution. In view of this, significant research is currently taking place, aimed at the minimization of the environmental footprint of EV charging infrastructure. Modern technologies such as the smart charging concept, sophisticated energy management schemes and the incorporation of ESS are thoroughly investigated, whereas the main focus of this research activity is on RES-based EV charging stations, as well as on the utilization of alternative energy sources, such as biomass and fuel cells.

4. Conclusions and Future Outlook

In this work, an in-depth overview of the environmental impact of road transportation is carried out, including the EU guidelines and a roadmap towards GHG emission reduction, as well as the application of innovative green technologies in the Transportation Sector. In particular, current trends in fuel consumption reduction are presented and discussed. Concepts and technologies such as thermal (waste heat) and kinetic energy recovery snd RES incorporation into conventional vehicles and EVs, as well as into EV charging stations, are also reviewed.

As regards the environmental impact, EU, US, China and other countries are concerned about road transportation effects; thus, international agencies and associations have set some strict goals and directives, in order to revert this negative situation. Significant initiatives have already been established across a large number of countries and cities worldwide, such as the Green Deal and the Paris Agreement. Furthermore, recent research works in both academia and industry have been analyzed, focusing on both on-vehicle (i.e., including the incorporation of RES, TEGs-based WHR, piezoelectric harvesters and regenerative braking systems) and off-vehicle (i.e., RES-based EV charging infrastructure, intelligent energy management schemes with a focus on demand prediction and optimal energy allocation) methods. The majority of the reviewed works present some rather promising solutions for road transportation regarding its environmental footprint.

However, despite the encouraging results showcased in the reviewed works, it is important to note that the majority of research in this field remains at the test or pilot level. This implies that while promising advancements have been made, further validation is required before widespread implementation can be achieved. Nonetheless, the global climate initiatives currently in place offer a favorable environment for the continued development and eventual commercialization of the proposed solutions.

In particular, the rapid progress in solar PV module technology holds great potential for the future adoption of VIPVs, which are projected to become increasingly prevalent in various transportation electrification applications, contributing to a significant decrease in GHG emissions from road vehicles.

Finally, the expansion of the EV charging station network plays a pivotal role in driving the mass adoption of EVs and further reducing GHG emissions. Governments worldwide have recognized the importance of promoting sustainable transportation and have implemented incentives and policies to encourage the development and proliferation of EV charging infrastructure. These initiatives aim to overcome the challenges associated with limited charging station counts and range anxiety by providing the necessary support to foster consumer confidence in EVs. As a result, the increased availability and accessibility of EV charging stations will facilitate the widespread adoption of EVs, leading to a substantial decrease in carbon emissions from transportation.

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Abbreviations

AC	Alternating Current
AEV	All-Electric Vehicle
AI	Artificial Intelligence
BEV	Battery Electric Vehicle
BMS	Battery Management System
BP	Battery Pack
CCU	Central Control Unit
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COP26	Climate Change Conference of the Parties
DC	Direct Current
DoD	Depth of Discharge
EIA	Energy Information Administration
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
F-gases	Fluorinated gases
FREVUE	Freight Electric Vehicles in Urban Europe
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HC	Unburned hydrocarbon
HEV	Hybrid Electric Vehicle
HV	High-DC voltage
HVAC	Heating Ventilation and Air Conditioning
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ICT	Information and Communications Technology
IEA	International Energy Agency
IEO	International Energy Outlook
IPCC	Intergovernmental Panel on Climate Change
LED	Light-Emitting Diode
Li-ion	Lithium-ion
LV	Low-DC voltage
MPPT	Maximum Power Point Tracking
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide
NO	Nitric oxide
NO_x	Nitrogen oxides
NZE	Near-Zero Emission
nZEB	(nearly) Zero Energy Building
OECD	Organization of Economic Cooperation and Development
PHEV	Plug-in HEV
PV	Photovoltaic
RES	Renewable Energy Sources
ROI	Return-on-Investment
SAE	Society of Automotive Engineers
SoC	State of Charge
TEG	Thermoelectric generator
US	United States

V2G	Vehicle-to-Grid
V2V	Vehicle-to-Vehicle
VIPV	Vehicle-Integrated Photovoltaic
WHR	Waste Heat Recovery
WLTP	World Harmonized Light Vehicle Test Procedure

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