energies

Review

Overview of Energy Harvesting Technologies Used in Road Vehicles

Jacek Caban [1,*], Jan Vrabel [2], Dorota Górnicka [3], Radosław Nowak [3], Maciej Jankiewicz [4], Jonas Matijošius [5] and Marek Palka [6]

1 Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland
2 Faculty of Operation and Economics of Transport and Communications, University of Zilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia
3 Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-524 Warsaw, Poland
4 PKP Cargo S.A., Grójecka 17, 02-021 Warsaw, Poland
5 Faculty of Transport Engineering, Vilnius Gediminas Technical University, J. Basanavičiaus 28, LT-03224 Vilnius, Lithuania
6 Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Nowowiejska 24, 00-665 Warsaw, Poland
* Correspondence: j.caban@pollub.pl; Tel.: +48-815-384-267

Abstract: Road transport is one of the most important factors for the national economy due to its universality and comprehensive possibilities of transporting people and goods. Unfortunately, from the energy point of view, it is also the most cost-intensive and has a negative influence on the natural environment. For these reasons, issues related to limiting the use of conventional fuels are very important, which results in reducing emissions from this sector, as well as reducing transport costs. This article presents currently used energy sources for propulsion of road vehicles, including fossil and alternative fuels, gaseous fuels and other energy sources such as fuel cells. The following section presents technologies that allow to recover some of the energy lost in motor vehicles and internal combustion engines used for their propulsion. The principle of operation of these solutions, their structure and their main features are presented. The last part focuses on discussing and identifying the most universal technologies for energy harvesting in vehicles and showing further directions of energy development in the automotive sector.

Keywords: alternative energy; micro sensors; thermoelectric generator; vibration energy; wasted energy

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1. Introduction

Currently, the world is struggling with climate and energy problems. The increase in energy and fuel prices affects not only producers and transport entrepreneurs but also the entire society. There are problems with the supply chains of various products and semi-finished products or raw materials, which results in a large increase in prices. Therefore, among others, for these reasons, they accelerate work on various alternative energy sources and new solutions, which were usually reserved for large energy sectors. Derkacz and Dudziak in [1] presented research on the energy sector in Poland in the years 2005–2020. Based on the conducted research, it was shown that the gross amount of savings strongly determines the gross amount of investments in the energy sector. This study [1] proved that it is not profits but investments that drive the development of private investments, which in turn influence the development of the energy sector and the entire economy in Poland. In turn, Jalowiec et al. [2] believe that the implementation of the Energy Policy between now and 2050 should facilitate the transformation of the coal-based electricity system towards a more sustainable and diversified energy mix. The authors [2] presented an analysis of surveys on basic matters related to climate and energy strategies which, in the opinion of respondents, were adopted in the EU. Unfortunately, a major role in making decisions about changes in the energy sector is taken by politicians who do not want to expose themselves to public opinion, which has a negative impact on changes in this sector. Figure 1 shows the forecast of the investment size in individual market renewable energy sources (RES) until 2050.

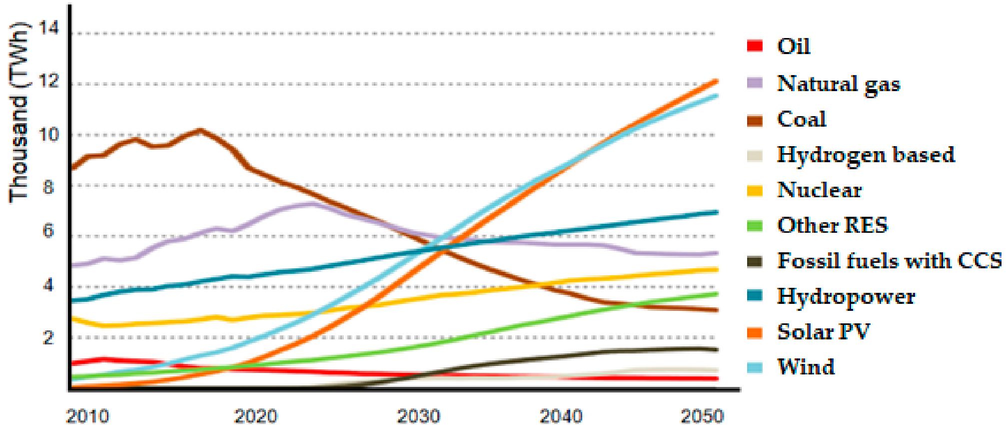

Figure 1. Global electricity production 2010–2050 by source in APC [3].

The energy transformation of many national economies is moving towards abandoning coal in favor of greater use of RES, including the share of wind energy [4,5], solar energy [6–10], hydro energy [11–15] and the development of alternative fuels, including biomass [16–22] and biofuels [23–27]. It is predicted that in 2050, the use of RES in electricity production may increase by as much as 70%. In Figure 1, we can see that photovoltaics installations and wind turbines have the largest market share (50% of electricity supply). There is a noticeable increase in the share of hydropower in the energy market, which, according to estimates, by 2050 is to become one of the main sources of electricity [2]. The use of natural gas (NG) appears to increase slightly, while the share of coal in electricity production will decrease significantly by 2050. Around 2030, it is assumed that hydrogen and ammonia will be able to be used as fuel to generate electricity, similarly to NG in gas engines and coal. From the point of view of climate policy, the origin, method of hydrogen production and the related CO_2 emissions are very important. The lower the CO_2 emission is, the greater the chances of using hydrogen in the energy sector are. There are several types of hydrogen identified by colors, and they depend on how they are obtained. Poland produces approx. 1 million tons of hydrogen per year, coming entirely from fossil sources, and it is the so-called gray or black hydrogen, which must be purified of methane. Green hydrogen obtained in the process of water electrolysis using energy from RES is the most desirable in the energy sector. Violet or red hydrogen is obtained in the process of electrolysis but in nuclear power plants. Another is yellow hydrogen, which is produced in the process of electrolysis using solar energy. In turn, blue hydrogen is produced from fossil fuels combined with CO_2 capture processes. Brown hydrogen is obtained on the basis of fossil fuels: lignite. There are also white hydrogen—coming from natural geological sources—and turquoise hydrogen—obtained in the process of pyrolysis of methane or in the process of processing waste plastics. The development of hydrogen and bio methane technology used to power vehicles in road transport in EU countries is recommended, for example, in the Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 [28,29]. In turn, the biofuels market is noticeable in each of the economies, but it depends on the local substrates used in a given area of the country or region. These tendencies are visible in numerous publications, such as [30–34]. Papers [30,31] focused on the issues of biomass production from wood waste and wood for energy purposes. Momayez et al. [32] used biogas digestate effluents for pre-treatment of rice straw in order to improve the production of biofuels. Rice straw was pre-treated at several temperatures—130, 160 and 190 °C—for 30 and 60 min and subjected to enzymatic hydrolysis, simultaneous saccharification and fermentation (SSF), as well as liquid anaerobic digestion (L-AD) and dry anaerobic digestion (D-AD) [32]. The highest improvement in hydrolysis and ethanol yield was 100 and 125%, obtained from straw at the highest process parameters and pre-treatment with biogas digestion wastewater. The best methane yield (24 and 26%) was obtained with L-AD and D-AD straw at process parameters of 190 °C and 30 min with biogas digestate effluent. Wang et al. [33] studied methane production from rural household digesters. The influence of various amounts of magnetite powder on the anaerobic co-digestion of pig manure (PM) as well as wheat straw (WS) was determined. Satisfactory results were obtained; with the addition of 3 g of magnetite powder, a maximum methane production of 195 mL/g total solids was obtained (i.e., an increase of 72.1%). To improve the AD efficiency in [34], a soil with the potential for interspecific electron transfer, buffering capacity and nutrients for microbial growth was used. It was confirmed that the cations contained in the soil are the main reason for improving AD efficiency. Therefore, the finding in this study can be a benchmark for the conversion of various bio-wastes by solid-state AD [34]. As you can see, the methane production process can be carried out in various ways and uses a variety of input materials. However, the use of methane as a fuel requires operational tests to confirm the effect of the gas on the components of the internal combustion engine (ICE). However, it is an interesting alternative to fossil fuels.

Figure 2 shows the energy mix in the EU, together with the planned changes.

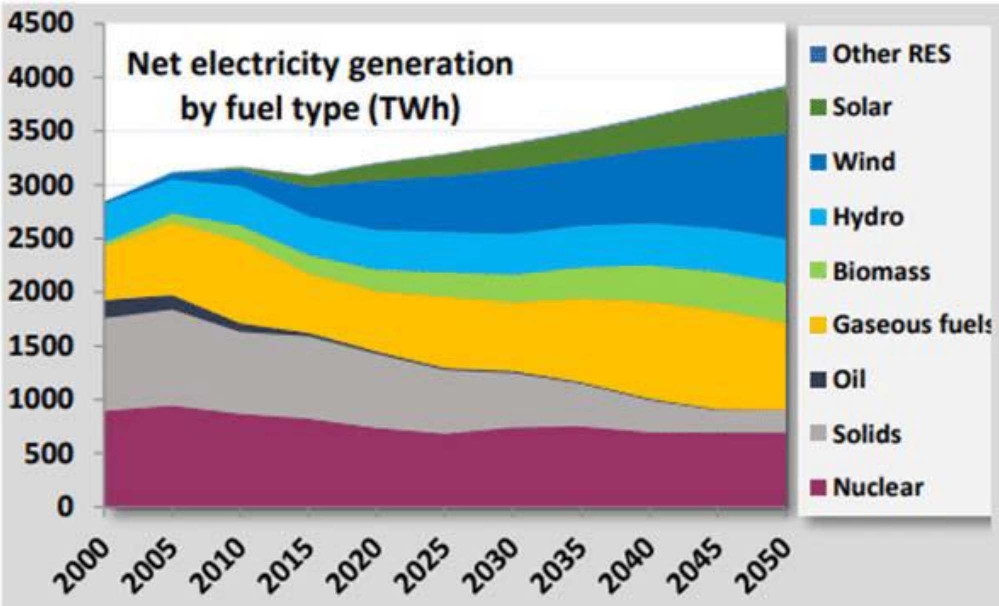

Figure 2. EU energy mix, including the planned changes [35].

As we can see in Figure 2, nuclear and gas fuels seem to be stable in the EU, as well as hydropower and biomass to a somewhat lesser degree. On the other hand, the expected share of RES (photovoltaics and wind farms) at the level of over 50% in the total energy mix is questionable due to their main and obvious disadvantage—i.e., high dependence on weather conditions. It is known that photovoltaic installations cannot generate electricity at night; however, during the day, the amount of solar radiation also varies, especially when it is located in the middle latitudes where EU countries are situated [36]. The area with relatively constant winds is the coastal zone and the Central European Plain; on the rest of the continent there are the same problems as with photovoltaics. Figure 3 shows the forecast of the emission reduction scenario by 55% by 2030 in the Polish energy sector.

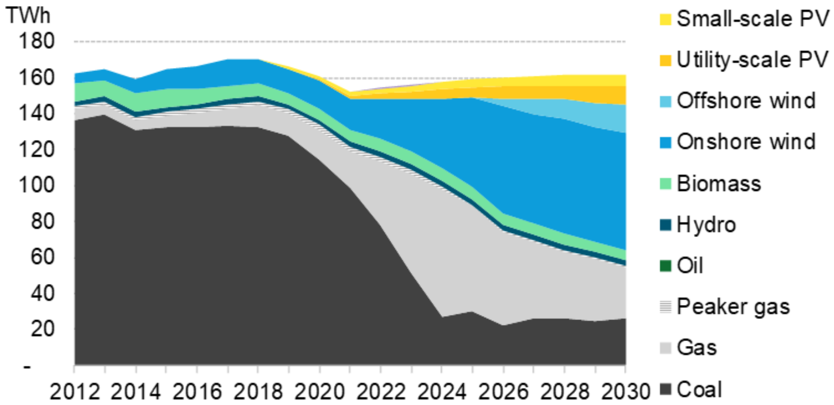

Figure 3. Poland's electricity generation mix, 55% scenario [37].

The projection presented, the 50% emission reduction target in 2018–2030 in Poland, could cause emissions in the energy sector to fall by 78%, while the 55% emission reduction target could reduce emissions by as much as 82% over the same period of time. Undoubtedly, there is a significant share of coal at the beginning of the forecast period, which is to be compensated by gas and renewable energy. On the basis of the forecasts presented above, there is a high hydropower potential. From the currently existing solutions for storing the produced electricity, the best results are obtained in the case of pumped-storage hydro power plants (widely used). Other technical solutions are compressed air and flywheels (rarely used in practice), as well as thermal energy stores and batteries. The spread of pumped-storage hydro power plants is favored by the surplus of energy generated at night by stable nuclear power plants, i.e., their efficiency is high exclusively in the complementary pair. With the exception of pumped-storage, all other methods have low energy storage capacity [36], but progress in the field of batteries could be a breakthrough in this sector. In the case of batteries, potential shortages of lithium and other metals used in the production of batteries may be a threat. As reported by Rehman et al. [38], the flexibility and storage capacity of hydroelectric power can improve grid stability and facilitate the deployment of other intermittent renewables, such as wind or solar power. Other authors also believe that hydroelectric power plants fill the energy gap created by the discontinuity of wind and solar energy [39–41]. Unfortunately, some regions create obstacles to the growth and use of hydropower due to the characteristics of this energy source [42]; promoting, at the same time, the construction of small and large hydropower plants is of fundamental importance [43]. According to Ma et al. [44], water energy turned out to be an important safeguard of socio-economic evolution. As pointed by Yang et al. [45], as power systems become increasingly dependent on an ever-increasing combination of intermittent RES, hydroelectric power plants are being required to regulate their frequency more aggressively. Hydro power plants have many advantages, the most important of which are the following: long service life of hydropower turbine sets [46]; low impact on the water ecosystem (fauna and flora); regulating the riverbed and reducing the risk of flooding [12]; aerating water and requiring care for water purity in the river; etc. However, they may affect the groundwater level [13], lowering or increasing it in the close vicinity of large hydropower plants, although this impact is difficult to determine.

One of the energy-intensive and cost-intensive sectors is the machinery sector, where technological processes consume huge amounts of energy. Therefore, there also is a lot of research on improving technological processes in this area [47–50], which also results in significant cost and energy savings.

Rising energy prices are changing the way of thinking about managing this energy in public buildings and the service sector or the hotel industry. Interesting research on energy consumption in a large hotel was presented by Orynycz and Tucki in [51]. The research shows that significant amounts of water and energy are wasted in the analyzed hotel facility, and the main sources of their losses have been identified [51]. As a result of modernizations and improvements, about 20% savings were obtained. In addition, the maximum possible daily savings resulting from the replacement of lighting in staircases and underground garages in the hotel building, along with replacement of the ventilation system, are estimated at approximately 68% for lighting and ventilation.

Another sector with high energy demand is the transport sector, both public and private. Due to the high rate of vehicles on the road, the transport sector is a major reason of fuel depletion [52]. In this sector, apart from the consumption of energy for work, we are dealing with its large dispersion and loss. In addition, the transport sector is a huge producer of pollutants and exhaust and dust emissions. Many scientific and research works have been devoted to the issue of pollutant emissions from means of transport, of which the following are worth mentioning: on greenhouse gas emissions [53,54], the impact of vehicle operation and the technical condition of the vehicle on exhaust emissions [55–61] and the type of fuel for vehicle propulsion [29,62–66].

Thus, we can see that the problem with energy consumption is visible in many sectors of the economy; therefore, any prospects for its saving or more effective use are an important issue for the sectors as well as consumers. This review presents development trends in the field of energy used in means of transport for their propulsion and the possibilities of saving fuel consumption and systems for recovering energy lost in means of transport. The latter aspect will be extensively described in the further part of the work, with the division into various ways of recovering mechanical and thermal energy and converting it into electricity that can be used directly in the vehicle. A schematic representation of the work structure is shown in Figure 4.

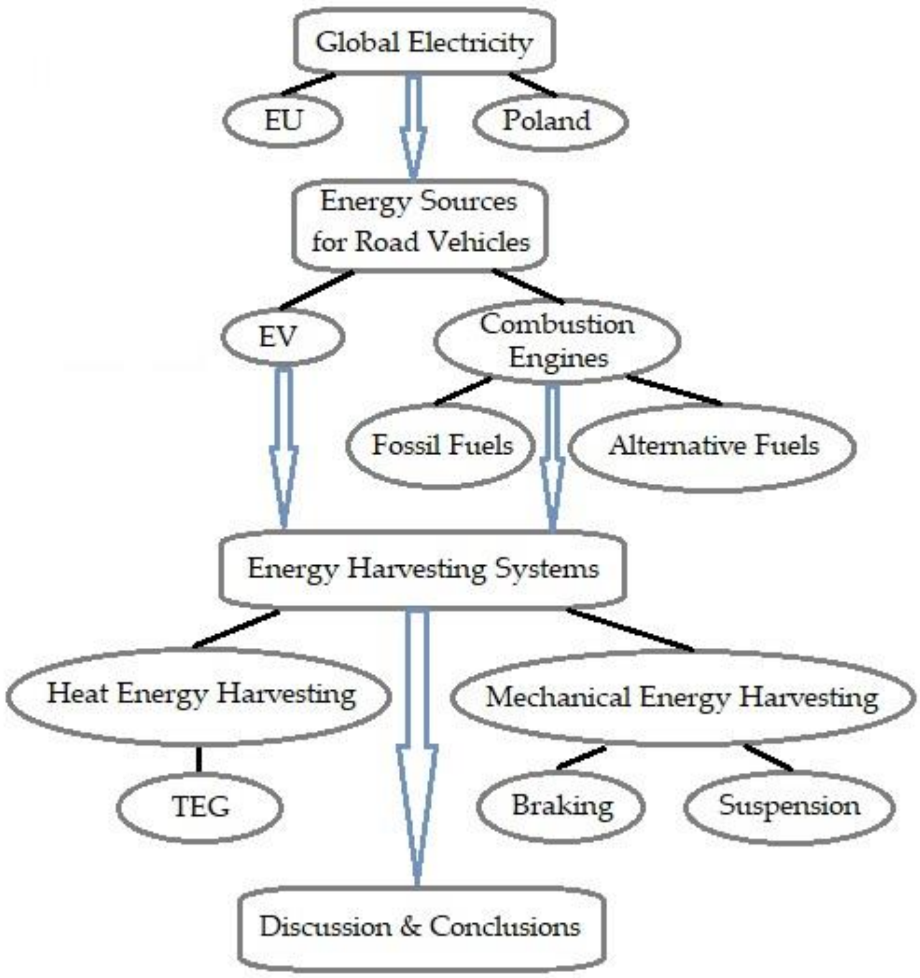

Figure 4. Schematic representation of the structure of this paper.

2. Current Sources of Energy for Road Vehicles

This chapter presents the current sources of energy (fuels) used to propel modern road vehicles. More than a hundred years ago, the internal combustion engine won the battle for the propulsion of motor vehicles. Currently, it is increasingly being displaced in favor of hybrid and electric systems. Although the road to complete electro mobility is still long, this direction is becoming more and more visible in many countries, but, above all, it can be seen in the offers of car manufacturers. There is a clear trend in moving away from combustion engines in many leading manufacturers, such as Toyota, Hyundai, Kia, Volvo, BMW or VW. Currently, work is underway on an EU regulation draft on the cessation of production of vehicles powered by ICE. The main premise of the project is the departure from the sale of vehicles powered by diesel engines from 2030 and petrol engines from 2035. Work on this project began in December 2018, and the regulations are to come into force from 1 June 2023. This is related to the expiry of the Motor Vehicle Block Exemption Regulation (31 May 2023). Despite this trend, ICE is still very attractive and has many supporters. The unquestionable advantage of the ICE is the possibility of its uninterrupted operation and the ease of fuel storage, which is important in off-road applications [67] (agriculture, construction and forestry machinery).

Diesel oil and gasoline remain the main fuel for ICE. However, due to the policy of moving away from fossil fuels and reducing exhaust emissions, there are two ways to improve the environmental performance of motor vehicles. One of the ways may be to modify the fuel with additives and mixing [68] and the use of the so-called alternative fuel. The second way is to change the drive systems. Fuels of this type include alcohols (such as ethanol and methanol), ethers, vegetable oils, animal fats and biodiesel as well as gaseous fuels (such as hydrogen, NG and liquefied petroleum gas (LPG)) [69]. Despite many research works [70–77], a big problem when using various alternative fuels to replace mineral diesel oil in diesel engines is the problem of its adaptation, resulting, for example, from modification of the fuel system or seasonality of selected biofuels. The latter factor is important in countries with high variability of weather conditions. On the other hand, biodiesel has long been considered a unique alternative fuel that can be used in a diesel engine with little or no modification [78]. Fuels in ICE, apart from their main function of providing energy, perform a lubricating function [23,71]. The fuel is involved in lubricating the precise pairs of the engine's injection equipment. In a study [71], the lubricating properties of fuel based on rapeseed oil esters and camellia esters were compared. Based on the tests, it was found that the highest electrical resistance occurs when lubricated with diesel oil, while the lowest coefficient of friction occurs when lubricated with camellia esters. In turn, in [23], the authors note that biofuels (such as rapeseed oil methyl esters and esters with the addition of oleic acid) have worse lubricating properties and may not be the best for fueling a diesel engine. Longwic et al. [73] presented research on the use of rapeseed oil and n-hexane mixtures in diesel engines with a common rail fuel injection system. The addition of n-hexane to canola oil significantly reduced its viscosity and surface tension [73]. This contributes to improving the process of preparing the combustible mixture and has a positive effect on the course of the combustion process. In one work [74], the impact of adding rapeseed oil fatty acid methyl esters (FAME) to diesel fuel on the specific fuel consumption and the emission of harmful exhaust components such as nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and carbon dioxide (CO_2) was assessed. During the tests, it was found that the addition of esters to diesel fuel significantly reduces the useful power of the engine, and higher FAME additives increase the specific fuel consumption. In addition, for the engine fueled with diesel oil with the addition of FAME, higher emissions of NOx, hydrocarbons and CO_2 were observed. On the other hand, much lower concentrations of CO and PM were recorded in relation to diesel fuel. It turns out that the use of biodiesel increases the specific fuel consumption and NOx, while reducing the emission of other toxic gas [75].

Research on the impact of biodiesel used in diesel engines with various fuel systems was studied also by [60,79]. In terms of fuel blending, bioethanol with gasoline [80,81], bio-ethanol with diesel [82,83], ethanol with diesel [84], biodiesel-ethanol and biodiesel-methanol blends can be used [85].

In a study [80], the effect of bioethanol (from soybean oil) and gasoline as a pre-mixed injection source on the combustion efficiency and emission characteristics of a single-cylinder dual-fuel engine was investigated. Dual-fuel combustion generates less NOx and soot than traditional mono-fuel combustion, while there is an increase in HC and CO emissions by premixing bioethanol or gasoline. As presented in [80], the biodiesel–bioethanol dual-fuel combustion mode was characterized by higher HC emissions than in the biodiesel–gasoline dual-fuel combustion mode, while the CO emission was at a similar level in both combustion modes. Pyrolysis oil is perceived as a substance extremely harmful to living organisms, which must be neutralized, but it has a relatively high calorific value; therefore, it can be treated as a potential fuel for spark-ignition ICE. Mixtures of ethanol and pyrolysis oil in a volume ratio of 3:1 (25% pyrolysis oil) can successfully replace ethanol in spark-ignition engines, especially in vehicles with a flexible type of fuel [81]. Paper [83] presents the results of testing dual fuel diesel engines fueled with fuel with a high bioethanol content—E85. Replacing diesel oil with E85 oil by 20% resulted in more than 2-fold shortening of the combustion time. With the increase in the energy share of E85 and the soot emission decreases in all ranges of the analyzed engine operation, unfortunately, the NO emission increased. The study [84] presents the results of co-combustion of the diesel–biodiesel–ethanol fuel mixture in a diesel engine with direct injection. Hydrated ethanol with a concentration of 89% alcohol was used. In the study, ethanol was added to a mixture of diesel fuel and biodiesel in a concentration of up to 50% with an increment of 5% [84]. With the increase in the ethanol content in the mixture, an increase in the ignition delay was observed (38.5% at full load), but the combustion time decreased. The proportion of ethanol fuel in the mixture causes an increase in NOx emissions due to the higher oxygen content and higher combustion temperatures in the engine cylinders. It was found that at full load, the uniqueness of the indicated mean effective pressure was close to 50% of ethanol in the fuel in the mixture [84]. Yilmaz and Sanchez [85] investigated the biodiesel–methanol and biodiesel–ethanol blends and compared them to biodiesel and standard diesel fuel. In general, blends of biodiesel and alcohol, compared to diesel, reduce NO emissions while increasing CO and HC emissions at up to 70% loading [85]. In addition, the blends of biodiesel and ethanol were found to be more effective than blends of biodiesel and methanol in terms of engine performance and emissions reduction.

Summing up the considerations on biodiesel, it can be said that biodiesel is produced in the form of rapeseed oil [86–90], sunflower oil [91–93] or palm oil [78,94,95] or obtained from wood biomass [96]. Moreover, mixtures of diesel oil with NG [63,76,97,98], CNG [99–101] and LNG [102–104] or diesel fuel with Brown's gas [105] are used.

Currently, models of dual-fuel engines that can run on diesel oil and natural gas have been successfully tested and successfully implemented. The dual-fuel mode of operation of the engine on natural gas/diesel fuels is a mode in which NG is introduced into the intake air before the intake manifold and then ignited by diesel fuel injected directly into the cylinder [97]. The dual-fuel mode of operation of the engine is characterized by lower compression pressure and a longer ignition delay compared to traditional diesel engine operation. Conversion of the popular ICE to gas fuel has positive effects in the form of reducing NOx and CO_2 emissions by 90–85% and 20–10%, respectively, and virtually completely eliminating PM and SO from exhaust gases [76,98]. A very important issue is the successful conversion of ICE to dual-fuel operation, which is supported by appropriate theoretical preparation and modelling. Much space is devoted to these issues in the literature. According to paper [63], the model made by the authors is recognized as a theoretical tool for the dual-fuel conversion model for engines in operation and has a practical application in the form of a quick application in industry. An interesting study on controlling the dose and time of NG injection in a dual-fuel engine was conducted by Ding et al. [97]. As demonstrated in the research on controlling the injection time of a natural gas engine, gas should be injected to the cylinder as soon as possible (better

15° CA to 30° CA) after closing the exhaust valve [97]. Review [99] presents the global background, perspectives and challenges related to gaseous fuel and natural gas vehicles, as well as the environmental and economic aspects of compressed natural gas (CNG) as a transformational fuel. The authors presented the main environmental advantages and limitations of the use of this fuel in road transport, such as limited number of refueling stations, vehicle range, limited loading space due to gas tanks or longer refueling time compared to petrol or diesel. The environmental benefits of using CNG in a dual-fuel gasoline engine are presented in study [100]. In turn, Szpica and Dziewiątkowski carried out research on the measurement of the catalyst conversion factor in an engine powered by CNG at various operating temperatures.

In [103], the authors assessed the environmental and economic properties of liquefied natural gas (LNG) as interim fuel to replace diesel oil in trucks. Tested vehicles with spark-ignition LNG engines turned out to be less energy-efficient (by approx. 18%) compared to their diesel counterpart, leading to a 7% increase in greenhouse gas emissions in the Well-to-Wheel (WTW) cycle. A reduction of up to 13% has been shown to be possible if LNG vehicles achieve comparable efficiency to diesel engines. The authors suggest that reductions in greenhouse gas emissions from LNG trucks will be possible when the efficiency of vehicles improves, and fleet operators will only gain financial benefits if the availability of public LNG refueling networks increases. Similar conclusions were reached by Jurković et. al. [102,104], paying attention to the environmental friendliness of LNG in the operation of vehicles. However, in order to comprehensively assess the environmental impact of switching from diesel to another alternative fuel source, such as LNG, it is necessary to quantify the lifetime emissions of each fuel. Another mixture fed into the engine's intake manifold is a mixture of hydrogen and oxygen (HHO), also known as a Brownian gas mixture. A small amount of gaseous hydrogen could also be produced in a car by splitting water in an electrolysis process, using the energy generated by a car power generator [105]. In [105], the combustion process of the fuel–air mixture in a 1.6 TD diesel engine and the fuel–air mixture for HHO gas combustion without additional regulation of the fuel supply system were studied. An increase in fuel consumption was observed after the additional injection of HHO gas into the fuel mixture, but a slight decrease in the content of CO, HC and PM was obtained. At low engine loads, the amount of NOx decreased; however, the increase in engine load resulted in a gradual increase in the NOx value. The authors concluded that the additional supply of HHO gas to the fuel mixture resulted in an improvement in the combustion quality of the air–fuel mixture and a greater environmental friendliness of the engine. These results are important for users of older vehicles that are not equipped with an additional system for reducing toxic exhaust components.

Another research area are mixtures of diesel fuel with butyl ester [106] and diesel engine with a diethyl ether [107] or n-hexan with diesel blend [73,108]. In [106], the physical and chemical properties of rapeseed oil butyl esters (RBE) and its mixtures of 10%, 20% and 30% RBE–diesel oil and rapeseed oil methyl esters (RME) were investigated. The obtained test results indicate that the additives of biological origin improved the energy performance of the tested engine but also slightly increased fuel consumption in comparison with pure diesel fuel. Increasing the concentration of the bio-component to 30% in mixtures of diesel oil and biodiesel (RME and RBE) leads to a comprehensive improvement of the environmental impact in comparison to pure diesel [106]. On the other hand, for mixtures with RBE, slightly higher concentrations of CO_2, HC and NOx in the exhaust gas were revealed, compared to RME mixtures of the same composition and pure diesel oil. An interesting study of mixtures of biodiesel with the addition of diethyl ether is presented in [107], where small portions of ether were added to a mixture of biodiesel and diesel oil (B30). The results of testing the properties of this mixture indicate a slight improvement in the density and acid number with a significant decrease in viscosity, pour point and cloudiness of the fuel mixture with the addition of 8% additive ratio by 26.5%, 4 °C and 3 °C, respectively, in comparison with the mixed fuel without the addition [107]. However, the calorific value decreases by about 4% with increasing the additive share to 8%. The study showed that the B30 supplement had a noticeable effect in increasing cycle-to-cycle fluctuations. The research conducted by Górski et al. [108] showed that the use of a mixture of rapeseed oil and n-hexane reduced the emission of nitrogen oxides (NOx). During the tests, the level of the main toxic substances (CO, HC, NOx) and CO_2, O_2 was measured for a diesel engine fueled with a mixture of rapeseed oil and n-hexane in comparison with diesel oil. It turned out that the addition of n-hexane as a non-reactive solvent to rapeseed oil causes a positive change in the physicochemical properties of the mixture, especially in terms of its density and viscosity [73,108].

A rediscovered direction of research is the use of ammonia as a fuel for self-ignition engines. Research in this area is presented by, among others, Boretti [109], Pyrć et al. [110], Sahin et al. [111] and Ubowska [112]—which studied reduction of greenhouse gases emissions for the supply of ship engines. Ammonia (NH_3) is the best hydrogen carrier in terms of safety and efficiency, which is why there are proposals to power internal combustion engines with ammonia [109–111]. Unfortunately, NH_3 is a difficult fuel to burn, so faster and more complete combustion is achieved when working in a dual-fuel system. The most promising fuel alternatives are either diesel injection ignition with indirect/direct NH_3 injection or jet ignition of a gasoline-like fuel (such as gasoline, CH_4, C_3H_8, H_2) with indirect/direct NH_3 injection [109]. The simulations show the prospect of achieving diesel-like power densities and efficiencies and controlling the load with the amount of fuel injected [109]. The co-combustion of diesel oil with a water solution of NH_4OH ammonia in the tested engine contributed to extending the period of ignition delay and combustion time and to increasing the rate of heat release [110]. Research [110] shows that the addition of aqueous ammonia solution led to a decrease in NOx emissions and an increase in CO and HC emissions and did not cause significant changes in CO_2 emissions. In turn, in a study [111], it was found that CO_2 emissions usually decrease at two selected engine speeds, but NOx, HC and CO generally increase. It seems that the key element for powering ammonia engines are specially designed high-pressure fuel injection systems.

As already mentioned, another way may be to change the drive systems of vehicles. This includes modifications to internal combustion engines or completely new alternative drives. Such a modification of gas engines has been described, among others, in the works of [113,114], hydrogen fuel cells [115–118] or battery and hybrid electric vehicles [59,119–122]. Hybrid systems are a combination of an electric motor and a spark-ignition or compression-ignition combustion engine. Electric vehicles (EV) are a new chapter in the automotive industry [123], which requires solving many challenges, such as modernization of the existing vehicle charging infrastructure [120], construction of a new one where it does not exist, and issues of technical diagnostics of EV [124–126]. In the case of EV, there is also a dispute about whether they are actually a zero-emission means of transport. This issue is discussed in more detail by Rievaj in [127]. The issues of emissions from various means of transport were also of interest to Rybicka et al. [128]. Ultimately, the question of the direction of changes in the dominant alternative fuel has not yet been settled, although hydrogen fuel cells and EV are becoming more and more popular.

3. Energy Recovery in Road Vehicles

The main reasons for reducing energy losses in motor vehicles is to reduce the fuel consumption of motor vehicles and thus reduce emissions [129–131], reducing the consumption of consumables [132–134] and increasing the efficiency and reliability of vehicles [135–138]. Part of the recovered lost energy can be used to cover the demand of other vehicle electronic systems. Automotive energy harvesting systems are usually employed to increase overall vehicle efficiency [139]. The main directions of recovery of energy lost in vehicles are heat energy losses [140–145], the energy obtained from the vehicle braking process [146,147] and the energy derived from damping vibrations in the vehicle suspension system [148–152]. The most popular energy harvesting systems are based on the following types of energy converters:

- piezoelectric [153–156];
- ferromagnetic materials [157];
- electromagnetic [158–160];
- thermoelectric [161].

A piezoelectric energy harvester is a device that converts the mechanical energy of a given environment into electrical energy [153,162]. In 1880, Pierre and Jacques Curie first described a piezoelectric material [163]; it consists of a solid material that is able to accumulate an electric charge as a result of mechanical deformation [164,165]. Currently, the piezoelectric effect is used to recover waste energy in various industry sectors, including motor vehicles. Vibration-based energy conversion using the piezoelectric effect has several significant advantages over other forms of RES, including low initial cost and less complicated wiring [154].

Vehicle thermoelectric generators (ATEG) are used in road vehicles to obtain waste energy from ICE exhaust gases [166]. There are three main components of the thermoelectric generators:

- heat absorber in contact with exhaust gases;
- thermoelectric modules converting heat into electricity;
- heat sink, the purpose of which is to increase heat transfer.

Thermoelectric generator modules (TEM) are an available device; basically, they consist of two pairs of n-type and p-type semiconductor legs that are connected electrically in series and thermally in parallel. This device converts a temperature gradient to electric voltage through the Seebeck effect. The legs connected by copper junctions are placed between two plates of electrical insulator—usually ceramic. A single 40 × 40 × 3.5 mm TEM can contain about 100 legs, capable of generating < 10 W with a heat flux of 240 Wm^{-2} and an overall energy efficiency of less than 5% [166]. The number of units in the TEG module is very different and depends on the type of vehicle and, thus, the size of the exhaust system. For passenger cars, it can be from 8 to 100, while for trucks it will be much more. For example, Frobenius et al. [167] installed 224 TEMs in a heavy duty truck exhaust pipe.

3.1. Waste Heat Recovery Technologies

As it is known, modern ICE are characterized by an overall efficiency of 40%, so most of the energy generated by them is dissipated, mainly through exhaust gases in the exhaust system and in the cooling system. As you may know, about one-third of the energy contained in the fuel burned in a light diesel engine is expelled with the exhaust gases through the exhaust system [168,169]. For this reason, numerous studies are being carried out to recover part of the thermal losses in the exhaust system and convert them into electrical energy stored in the vehicle's battery. The most important thing, however, is the assessment of the heat source because the nature of the exhaust flow changes during the engine operation [170]. According to Wang et al. [144], significant energy savings can be achieved by proper recovery of waste heat from ICE. Among the various waste heat recovery technologies in vehicles, the TEG has attracted much attention among researchers around the world [140,141,170–174]. Its high reliability is due to its compact design (without any moving parts), and the ability to convert heat directly into electricity is another noted advantage.

The diagram of the exhaust system in the ETEG thermoelectric generator is shown in Figure 5. This system includes TEG modules and channels of the heat source and heat sink through which the engine exhaust gases flow. Twenty TEG modules (10 on each side) were installed on both sides of the engine exhaust system [140]. The exhaust channel system serves as the heat source, and the air flows through the cooling channel (upper and lower exhaust channel) as a heat sink. The presented TEG module consists of a total of 160 TEG units, electrically connected in series and thermally in parallel.

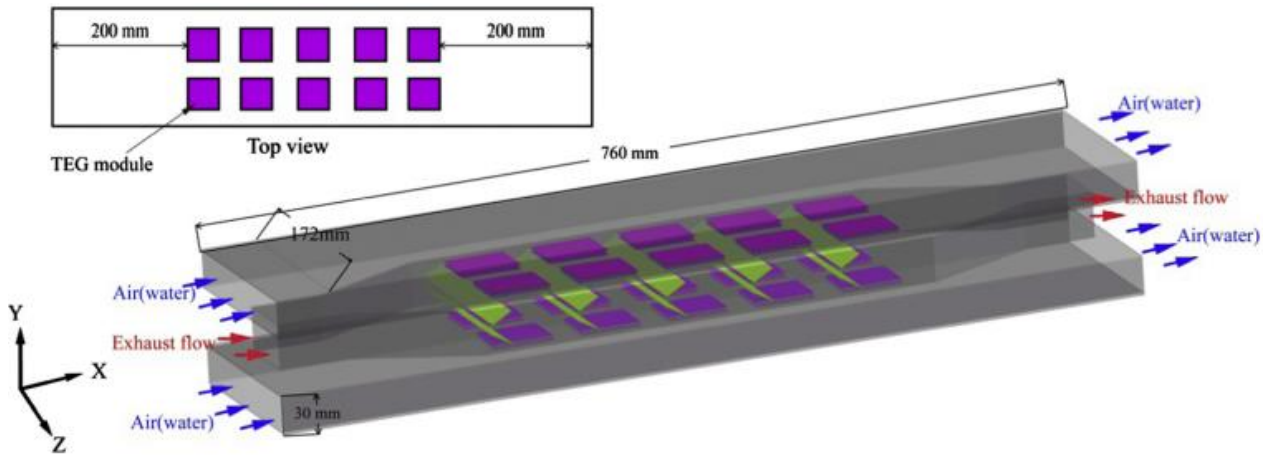

Figure 5. An example of a thermoelectric generator system for energy recovery from ICE exhaust [140].

Stobart et al. [175] investigated an ATEG with 16 TEMs in a square arrangement (4 columns each containing 4 TEMs; here, the term column refers to the position perpendicular to the direction of the engine exhaust pipe), achieving a maximum power output of over 30 W. The following dimensions were selected for the modeled TEMs: $65 \times 65 \times 4$ mm^3, to mimic commercially available HZ14®TEMs (supplied by Hi-Z Technology) [175]. This study also used computational fluid dynamics (CFD) calculations to predict in detail the impact of design parameter choices. In addition, the study aimed at validating the CFD calculations using a mathematical model to accurately predict the TEG power output. Heat transfer and pressure drop studies for six structures of internal heat exchangers in a passenger car with a 1.2 dm^3 petrol engine using CFD modeling were also carried out by Bai et al. [176]. It has been shown that the serial plate structure provides the greatest heat transfer and the greatest pressure drop, and that there is a compromise between these parameters. In turn, Su et al. [177] analyzed three internal structures of heat exchangers for TEGs based on car exhaust: fishbone, pleated and diffuse. Studies have proven that the accordion-shaped design provides better uniform temperature distribution in the system. Unfortunately, both of these studies do not present specific values of electric and net power. In another study, Liu et al. [178] conducted an analysis of the temperature distribution in a heat exchanger mounted in the exhaust system of a naturally aspirated spark ignition engine with a capacity of 2.0 dm^3. In this study, two systems of internal heat exchangers with different geometries were compared, the first in the shape of a fishbone and the second with a chaotic structure. The authors concluded that a heat exchanger with a chaotic structure achieves better results (maximum electrical power of about 180 W).

The transmission of energy from the engine exhaust of two types of vehicles, a 3.5-ton van and a heavy 40-ton vehicle, at constant speed and the World Harmonized Transition Cycle (WHTC) is presented in [143]. The simulation evaluated the effect of two different designs of heat exchangers, either with flat fins or staggered stripes, on electrical power and net power output. The influence of the height, spacing and length of the fins, as well as the width and length of the heat exchanger and the height of the thermocouple legs were investigated. The analysis was carried out under fixed conditions, assuming typical extra-urban driving speeds, mass flows and exhaust gas and coolant temperatures for both vehicles. In both tested heat exchangers (flat and offset), a compromise is needed to obtain high electrical power and net power simultaneously. With the criteria used, the flat fin exchanger provides better performance than offset ribbons, especially as a result of the pumping force. Analysis of the size of the TEG shows that doubling the length for maximum electrical power is more efficient than doubling the width [143]. However, doubling the width of the exchanger is more efficient in terms of net power output. It was found that for typical domestic driving conditions, as well as for the heat exchanger and the external dimensions of the TEG found in the parametric test, the efficiency of energy harvesting is low [143]. Thus, the best energy recovery efficiency recorded is around 2%, with an average thermoelectric material efficiency of around 4.4% for a light vehicle [143]. Moreover, for a heavy truck, the results of the parametric analysis indicate the achievement of over 800 W of electric power. In this way, this energy can be used to generate the vehicle's required electrical network. Thus, this can be used in determining the requirement for the electrical network of a given vehicle. The potential profits from the use of TEG modules in a steady state Sports Utility Vehicle (SUV) were analyzed by Karri et al. [179]. In their research, they generated electricity in the range of 100–450 W, which translated into fuel savings of about 2.3%. It is obvious that the best results were noticed in trucks, which produce more exhaust gases, which does not mean that passenger cars are not interesting, especially those used mostly in city traffic.

In a study by Lu et al. [180], two types of structures related to the improvement of heat exchange from the exhaust gas of a car with a spark-ignition engine were tested. The first type of structure is rectangular staggered tape fins, and the second structure consists of metal foams. It was shown that the electrical power obtained for metal foams was definitely higher (in the range of approx. 130–294 W) than for offset tape ends. Unfortunately, with metallic foams, there is a greater pressure drop, and although the total system output power increases, the resulting net power output is lower.

In the work of Ibrahim et al. [181] the characteristics of car exhaust heat recovery by TEMs using a rectangular exhaust gas exhaust system were investigated. They found that by placing a porous material inside the flue exhaust system, the conversion efficiency of thermoelectric energy increases the heat exchange from the gas stream flowing in the hot side duct to the surface of the TEM. Kim et al. [141] used the exhaust system of a six-cylinder diesel engine with turbocharging as a source of heat. The ICE worked in various conditions determined by three different engine speeds (i.e., 1000, 1500 and 2000 rpm). The tests determined the influence of the flue gas flow rate on the TEG output power. Then, based on the analysis of the experiment results, a contour map was developed for the TEG output power, expressed as a function of engine load as well as rotational speed. As a result, the output power of the TEG module was found to increase with engine load or engine speed. Summing up the research, the maximum output power was 119 W at 2000 rpm with BMEP 0.6 MPa, and the maximum energy conversion efficiency was in the range of 0.9–2.8% [141].

In [182], the efficiency of waste heat recovery for the TEG module equipped with a porous plate-type carrier (perforated plate) was experimentally tested. The obtained results of experimental studies showed that at the engine speed of 1400 rpm, the maximum power output of 98.3 W was obtained with the lowest insert porosity (0.121), and with the optimal insert porosity (0.416), the maximum energy conversion efficiency was 2.83% [182]. Increasing the conversion efficiency and the output power of the tested TEG module can be achieved by using a porous internal medium, the values of which are 0.461 and 0.32, respectively. It was ultimately shown that a plate-type porous medium with a porosity greater than 0.32 should not be used in the current configuration of the TEG module because the back pressure in the passenger car exhaust system would exceed the allowable limit of 3 kPa.

Figure 6 shows an exemplary configuration of the TEG system with a preceding diesel oxidation catalytic converter (DOC).

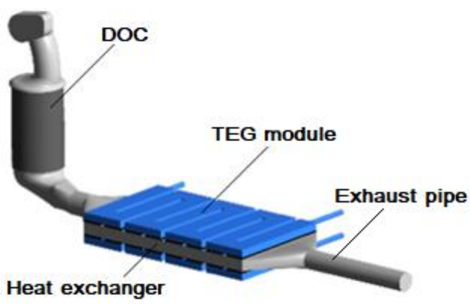

Figure 6. TEG system with a preceding DOC.

From the CFD simulation, the surface temperature distribution on the hot and cold sides is obtained as shown in Figure 7. More details on the applied equations and numerical CFD simulations of the model can be found in [183].

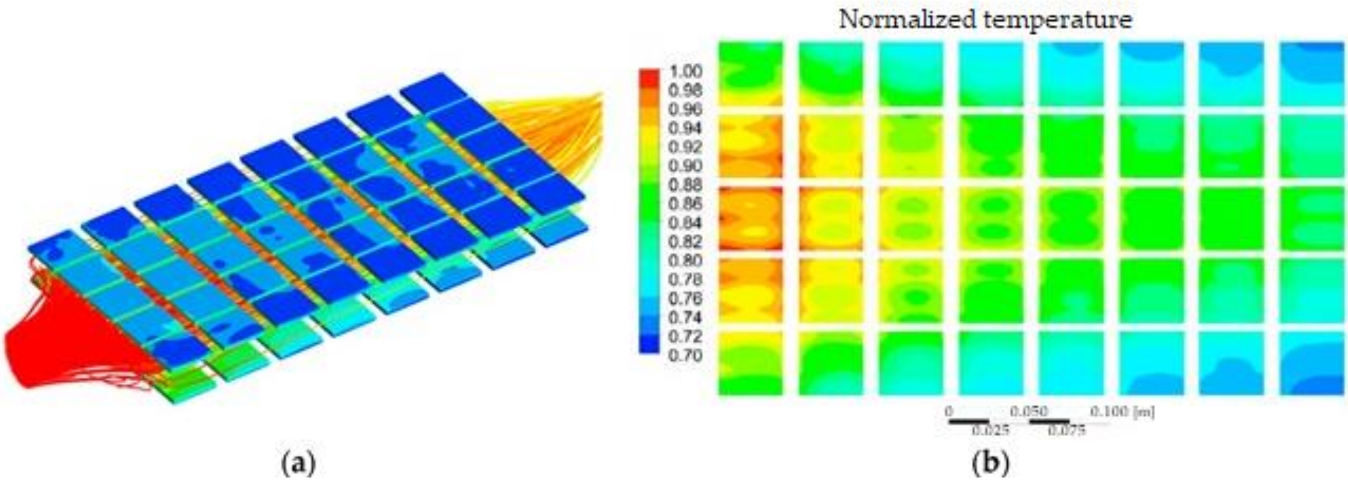

Figure 7. (**a**) Simulation of flue gas flow in the TEG module and (**b**) temperature distribution in the modules (upper surfaces) [184].

The scientific literature presents numerous studies devoted to the modeling of thermal waste energy harvesting systems in automotive applications. Meng et al. [185] developed a multi-physics control-volume TEG model for waste heat recovery from automobile exhaust. In these studies, the constant state of exhaust gas was taken into account, and the thermoelectric material used was Bi_2Te_3. This study analyzed and discussed in detail the number and size of thermocouples used in the system and the direction of flow in the heat exchanger on the cold side. Temperature inequality occurring along the flow direction and its impact on TEG parameters are presented. In the articles by Kumar et al. [186,187], a numerical model was developed for the TEG corresponding to the conditions found in a light commercial vehicle. Another mathematical model of TEG was presented by Wang et al. [144]. Their model operates in a steady state and uses the engine exhaust in the vehicle as a heat source. Yu et al. [188,189] developed a numerical model based on which they found that the performance of the TEGs improved as the driving speed of the pickup vehicle increased. A range of power values of 18–220 W was obtained when the driving speed was increased from 20 km/h to 120 km/h, and the transient behavior of the TEG modules in various driving conditions was tested.

In turn, Ma et al. [190] tested the performance of a TEG system equipped with plate-fin heat exchangers for the effect of longitudinal vortex generators (LVGs). These tests showed that there is great potential at LVGs to improve the efficiency of TEG modules. The input heat and open-circuit voltage in the TEG module with LVG under basic system operating conditions are increased and range from 41% to 75% compared to the normal smooth TEG channel [190].

Research in the field of TEG is not only the domain of scientific centers but also of automotive companies, who are working tirelessly on solutions for energy recovery in the vehicles they produce. For example, BMW has strategies for commercializing vehicles with TEG installation and combining TEG and catalytic converter functions to improve system compactness [191]. They were also involved in the production of highly efficient and environmentally friendly thermoelectric modules. On the other hand, General Motors has developed a TEG with a rectangular configuration, aimed at the Chevrolet Suburban, which includes two different types of TEG modules [192].

3.2. Braking Energy Recovery

Parallel to the progress of energy management technology in the propulsion system [193], work is underway on the recovery of energy from the vehicle braking process [139,146,147,194,195]. Braking energy in a hybrid vehicle can be recovered and recycled by the regenerative braking system [196–198], which significantly saves energy and reduces the emission of harmful gases into the atmosphere. In the literature, you can find many works that refer to the recovery of energy from the braking force. Most of the studies, however, refer to EV [194,196,199,200] or hybrid vehicles [201–203], and only a few refer to those powered by an ICE [147,204] and other machines [205]. The reason for this may be achieving significantly lower benefits compared to hybrid or EV. According to Held et al., test cycle simulations with a variable speed profile show that 7% of energy can be saved without increasing travel time or deviating from the normal driving pattern [204].

Thanks to the use of the regenerative braking system, it is possible to use the engine to convert the kinetic energy of braking into electric energy and store it in the vehicle's battery. The electric energy obtained in this way can then be used for further driving. In this case, we obtain a more efficient use of electricity, which translates into a greater range of the vehicle. For these reasons, it was important to maximize the recovery of braking energy under safe braking conditions and was the main goal of research on energy flow management in hybrid and electric vehicles.

The regenerative braking strategy for rear-wheel drive EV proposed by Zhang et al. [206] improves the efficiency of regenerative braking up to approx. 47%. In the experiment of Qiu et al., this model was experimentally verified, and the obtained results confirmed the effectiveness of this strategy for a constant input of 58.56% and for a dynamic action of over 69% [207]. In turn, Itani et al. compared flywheels with supercapacitors as the second source of energy for EV driven by the front axle [208]. Their results showed the superiority of ultra-capacitors in terms of mass, specific energy and specific power. Reusing braking energy was more convenient and safer for the batteries during regenerative braking [208].

Lu et al. [209] presented research on a strategy for controlling the regenerative braking of a fully electric composite energy bus based on the use of engine performance. In this study, they achieved a relative increase in braking energy recovery of nearly 48%. Research results conducted by Chu et al. [210] show that based on the World Light Vehicle Test Cycle (WLTC), the energy recovery rate can reach 30.4%, while ensuring braking safety even when braking with high intensity. Similar values for the WLTC test were obtained by Sandrini et al. [211], where the energy saved was 29.5 to 30.3 percent. In this study, the braking energy recovery logic was tested using a simulation on a front-, rear- and all-wheel drive compact car.

In the research presented by Yang et al. [194], a hybrid electric vehicle system was used, the schematic diagram of which is shown in Figure 8. When high power demand is required, both motors can work simultaneously. Both axles of the vehicle are equipped with electric motors, which ensures good dynamics in purely electric mode, and it is also possible to obtain more energy during braking.

The vehicle controller is responsible for collecting data on vehicle speed, brake pedal position and master cylinder pressure, among others. After detecting the signal from the brake pedal, the driving status of the vehicle is quickly determined; then, the control signal via the Controller Area Network (CAN) bus is sent to the downstream controller [194]. The downstream controller, on the other hand, identifies the correlation according to the control signal, after which it sends signals to the hydraulic control unit and the motor control unit according to a predetermined algorithm to execute the control instructions from the driver.

Figure 9 shows the graph of energy consumption, where the losses of individual system elements in the braking process are marked.

As shown in the diagram in Figure 9, energy losses occur in every element of the system, starting from the wheels of the vehicle, through the CVT transmission, to the motors and the energy stored in the battery. Other energy losses not related to the braking process, such as motion resistance or wind resistance, are omitted at this point.

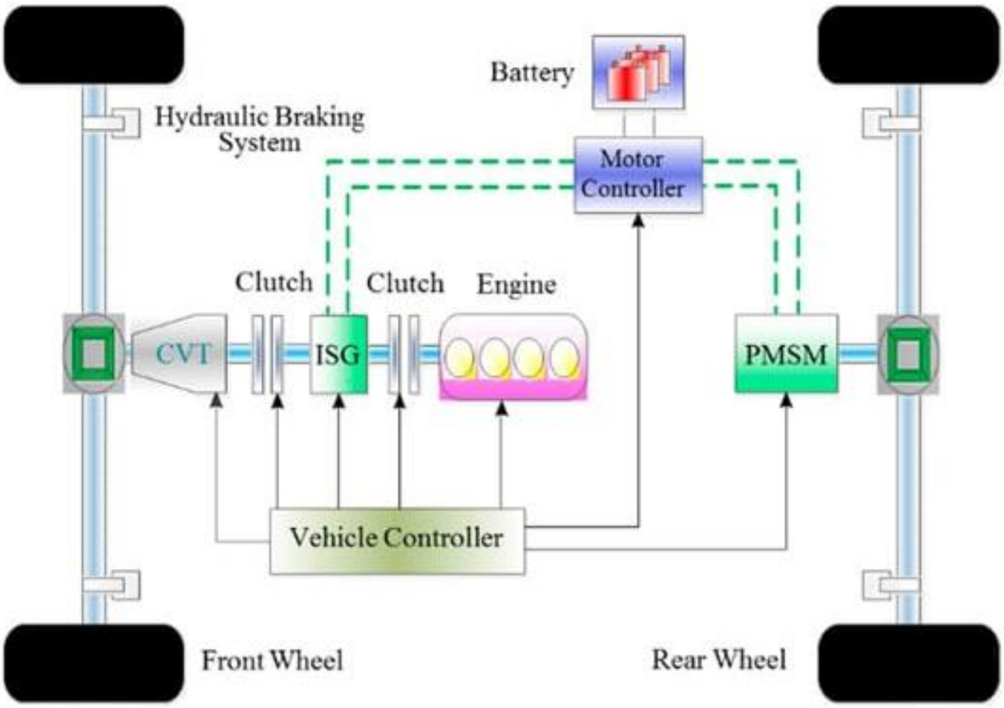

Figure 8. Schematic diagram of dual motor hybrid electric vehicle [194]. CVT—continuously variable transmission; PMSM—permanent magnet synchronous motor; ISG—integrated starter generator.

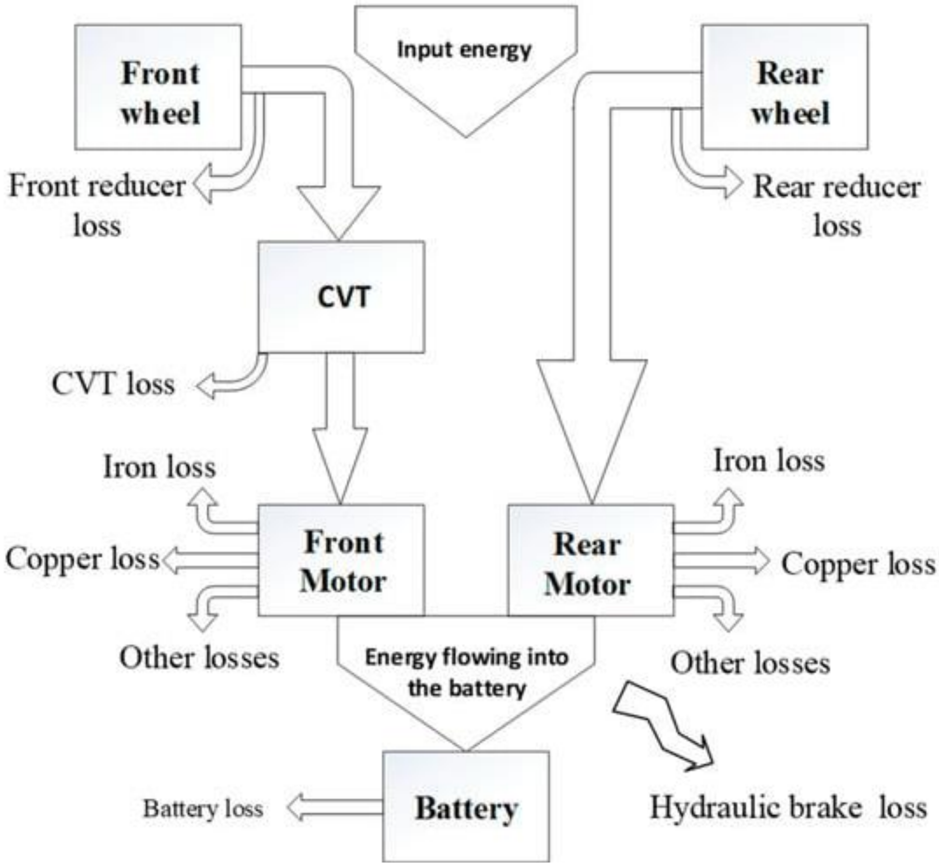

Figure 9. Graph of energy consumption and losses during braking [194].

Another braking strategy analysis for a Formula SAE electric race car, for steering the vehicle wheels on the front and rear axles, was presented by Henao-Muñoz et al. [212]. The proposed braking strategy is aimed at increasing the recovery energy through the appropriate distribution of braking forces between the wheels on both axles of the vehicle. In this study, three braking strategies were compared with regard to braking energy yield and vehicle stability. The results of the simulations show that the proposed management strategy allows for greater energy recovery while avoiding blocking both the rear and front wheels of the vehicle [212].

Similar studies for a Formula SAE electric racing car were conducted by Dolara et al. [213]. All components of the EV and hybrid lithium–ion batteries as well as ultracapacitors are used to store the kinetic energy of regenerative braking in the Kinetic Energy Recovery System (KERS) [213]. Their results show the ability of the converter to operate in resonant mode in both boost and step down modes. The noted disadvantage of this solution is the presence of high current peaks in the resonant coil. On the other hand, the use of more than one interlaced converter and the adoption of an appropriate efficiency factor enable the correct operation of this system.

Summing up the considerations on the distribution of energy recovered during braking, the following graph of energy distribution in an EV can be generated (Figure 10).

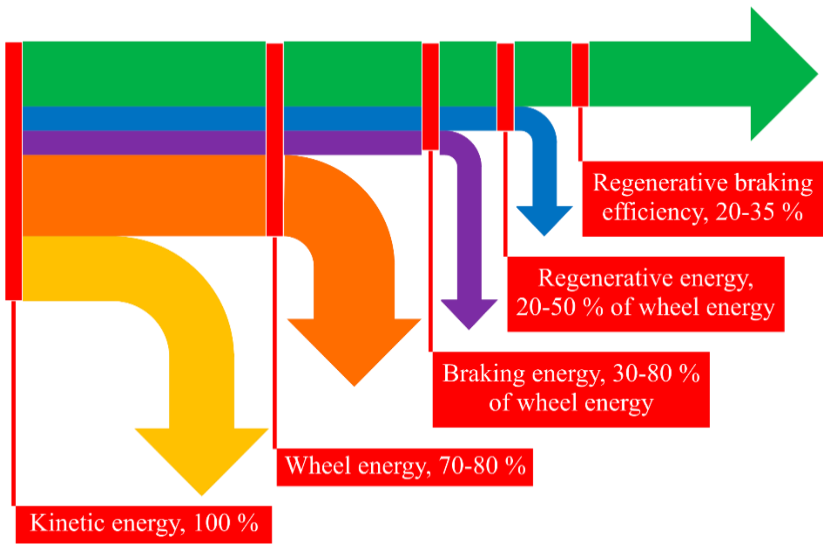

Figure 10. Energy distribution in EVs [214].

Analyzing the graph in Figure 10, it can be concluded that braking can absorb from 30% to 80% of the vehicle's kinetic energy. This share depends on energy management and the implementation of the braking process. Due to the increased range, extended mileage and increased efficiency of electric vehicles, it is so important to properly manage and recover energy. In addition to the overall improvement of the vehicle's efficiency, regeneration can significantly extend the service life of the braking system, because in such operating conditions, the mechanical parts of the system wear much more slowly [214].

3.3. Energy Harvesting from Vehicle Suspension

Regardless of the drive that a motor vehicle is equipped with, each has a suspension system whose task is to dampen vibrations from the ground in order to ensure adequate vehicle stability, safety and comfort of passengers. That is why this vehicle system can also be used to obtain additional energy, which under normal conditions (without recovery devices) is damped in the suspension and consequently lost. Due to the fact that only 12–30% of the energy contained in the fuel is used to propel the vehicle in order to overcome the friction of the road surface and air resistance [215], and one of the main losses is the dissipation of vibrations in the suspension (shock absorber) [216], such an important issue is the technology of obtaining energy from the vibrations of the vehicle suspension system [217,218].

As shown in study [219], for a medium-sized vehicle moving at a speed of 96.5 km/h, the average power obtained from the suspension system is in the range of 100–400 W, on B- and C-class roads. As presented by Zhang et al. [220], based on the tests carried out by Audi AG, it is possible to recover energy with an average power of approx. 150 W from the energy harvesting system. Large differences in the presented values of the obtained power occur due to the type of the test section of the road on which the vehicles were moving. Thus, for a passenger car moving on a new section of the German motorway, it is only 3 W, while on an uneven national road, the energy efficiency obtained from the system was even 613 W. In turn, Li et al. [216], show that with optimal load resistance (at 7.5 Ω) and harmonic excitation with an amplitude of 8 mm and a frequency of 2 Hz, a maximum of 248.8 W of instantaneous power can be obtained with an average of 114.1 W and a maximum of 38.81% efficiency of energy obtained from the vehicle suspension system. In cars, collecting dissipated kinetic energy during damping can save fuel by about 2–10% of the car's total fuel consumption [221]. Figure 11 shows the possibilities of fuel savings due to the use of systems for obtaining kinetic energy during damping for various types of vehicle.

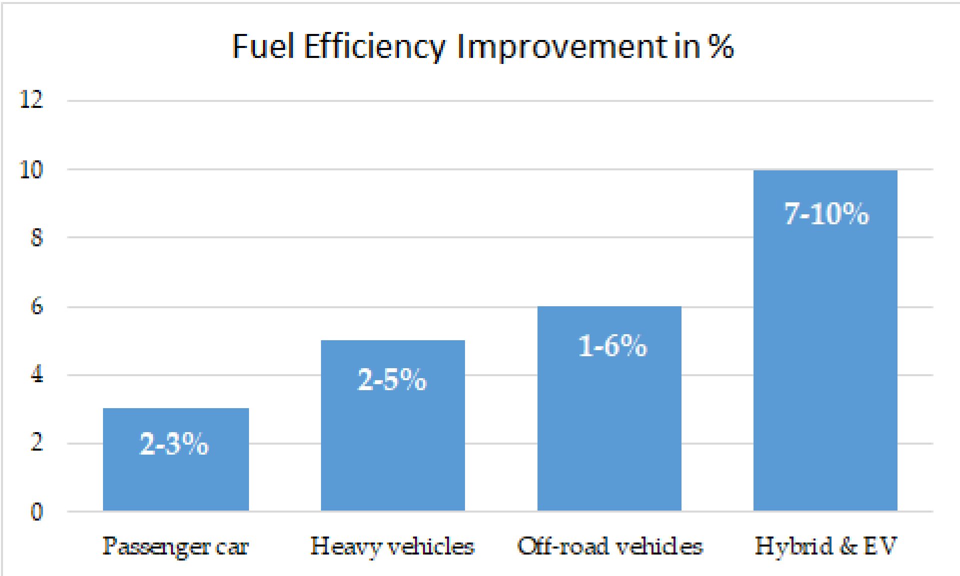

Figure 11. Fuel savings for different types of vehicles using energy harvesting systems.

Analyzing the data presented in Figure 11, it can be concluded that off-road vehicles and trucks as well as overloaded vehicles show a greater potential for fuel savings (up to 6%) compared to passenger cars, which give only a half of this result, and that is up to 3% fuel savings. However, as shown in Figure 11, the best results can be obtained with electric and hybrid vehicles. This is due to the differences in vibration intensity levels for individual vehicles. For this reason, energy harvesting systems from the suspension system should be of interest primarily to fleet customers.

The key element that converts the mechanical energy of vibrations into electrical energy in the suspension system is a special energy shock absorber. It mainly includes two elements: the energy conversion unit (linear or rotary electric motor) as well as the transmission devices (from reciprocating to rotary motion) [222]. Therefore, vibration energy flows into the vehicle's suspension system, causing the shock absorber piston rod to move vertically up and down sequentially. Electricity could be generated from these perpendicular oscillations in two ways: directly by the linear electromagnetic harvesters or indirectly by the rotary electromagnetic harvesters [223]. Schematics of various electromagnetic regenerative shock absorbers used in the vehicle suspension system are shown in Figure 12.

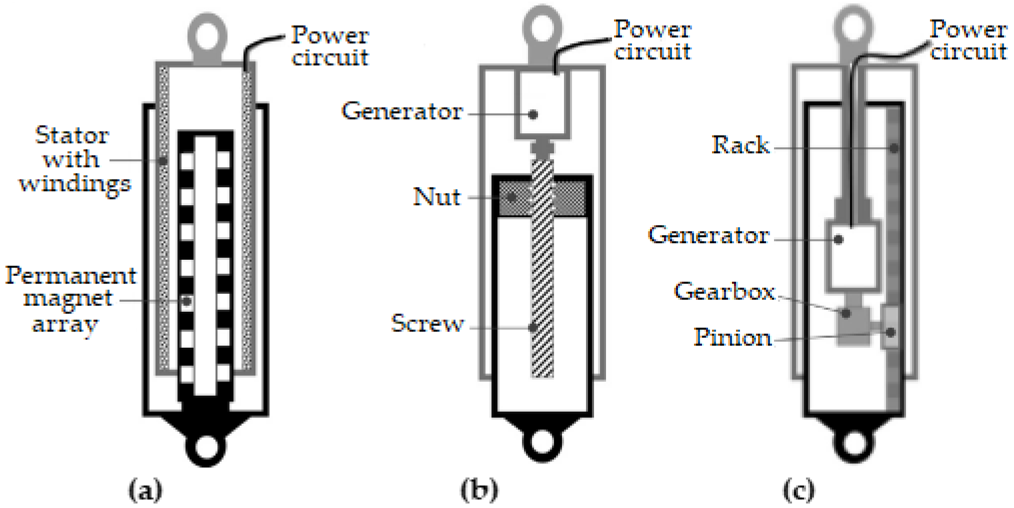

Figure 12. The electromagnetic regenerative shock absorbers (**a**) linear motor, (**b**) ball screw and (**c**) rack-pinion.

Zhang et al. [220], used an electro-hydraulic shock absorber to collect energy in off-road vehicles, thanks to which they obtained an average regenerative power of 110.6 W. They also showed that a trade-off is necessary between energy harvesting characteristics and shock damping. Li et al. [216] showed the construction of energy-receiving shock absorber receiving energy and the optimization of the control system, according to the diagram shown in Figure 13a. The construction of the shock absorber consists mainly of two elements—the motor and the ball screw. The task of the ball screw is to transform the vibrations that are generated between the vehicle body and the chassis into the rotation of the motor. The electric motor mounted in the shock absorber acts as a power generator that converts the kinetic energy of the suspension system into electricity, which is stored in the battery for further use, while ensuring the damping force [216] and proper vehicle stability.

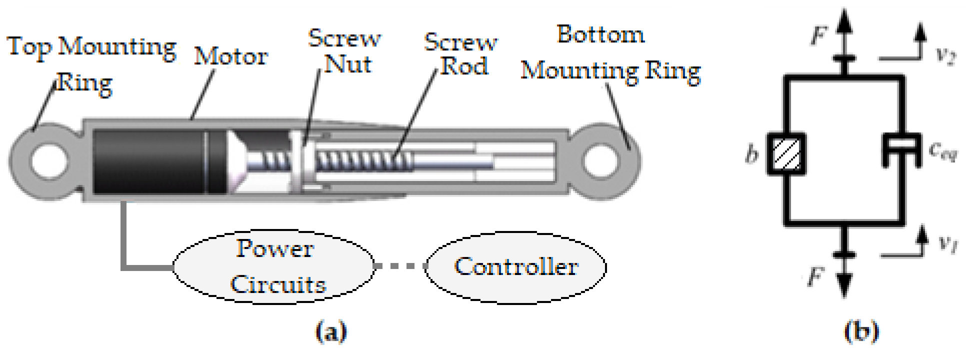

Figure 13. Structural diagram of the ball screw of the shock absorber—(**a**) and equivalent to the dynamic model—(**b**).

Since the system is affected by the moment of inertia of the motor rotor and the screw rod, the shock absorber for energy harvesting can be treated as a conventional oil shock absorber connected in parallel with an inerter, as shown in Figure 13b [222]. The individual symbols marked in the figure mean the following: F is the total shock absorber force; v_1 and v_2 are vehicle body and chassis velocities, respectively; b is inertia value; and c_{eq} is the equivalent damping coefficient. The PMSM generator (synchronous motor with permanent magnets) and the buck-boost converter, which is used to collect electricity, bring positive effects. Based on the test results, it can be said that the proposed control system and control strategy were characterized by a high response speed (i.e., 4 Hz) and a small tracking error, which amounted to 6.44%, compared to the set value of the damping coefficient [216]. It was found that this is a good basis for further research on the energy-harvesting semi-active suspension system [216]. In addition, the tests showed a high efficiency of energy collection from the tested suspension, ranging from 40.72% to 70.55% with sinusoidal excitation and random road excitation.

In the studies presented in [223], it was shown that vehicle vibrations caused by road irregularities can produce an average power of 350 W for a medium-sized passenger car (equipped with four energy-harvesting shock absorbers). However, for larger vehicles, harvesting power can be significantly higher than that of a sedan vehicle. The regenerative electromagnetic shock absorber has a relatively small load capacity, so it is more suitable for passenger cars, minivans, etc. An electro-hydraulic shock absorber can provide more damping force that is typically required in off-road vehicles. Therefore, it can be concluded that there is a large potential for recovering energy dissipated from the vehicle suspension system, which can be used to power, among others, comfort-enhancing systems. More detailed information on the collection of dissipated energy from the vehicle suspension system and the design of systems for energy harvesting can be found in the available scientific literature [216,219,221,224]. Figure 14 shows an example of the position of the shock absorber equipped with the energy harvesting system on the rear axle of the minivan vehicle.

Figure 14. Location of the shock absorber to collect energy in the minivan vehicle [219].

According to Al-Yafeai et al. [225], for passenger cars moving at a low speed of about 47 km/h, about 200 W of power dissipated in the suspension shock absorbers was recorded. Other studies presented above also confirm the high potential of generating energy in the vehicle suspension system. The energy yield increases depending on the type of vehicle (passenger car, van, truck) and the type of surface on which it moves. Therefore, this amount of energy cannot be ignored and is worthy of interest as well as harvested from the system.

As the presented literature research has shown, the energy yield from the vehicle suspension system, depending on the type of vehicle and the harvester used, is quite diverse. The ranges of recovered power range from several dozen watts to over 600 W, but, on average, it is up to about 300 W for a medium-sized passenger car. This energy can be used to power various electrical systems in the vehicle, such as comfort devices.

4. Discussion

Road transport is responsible for about 70% of total greenhouse gas emissions from transport [226]; the rest is mainly due to sea and air transport. The main air pollutants from the transport sector are harmful dusts and gases, which include carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), benzene, methane (CH_4), particulate matter (particulate matter (PM)), lead (Pb), platinum, ozone and dioxins. Particulate matter is composed of a center core of elemental carbon (soot) and adsorbed organic compounds including PAHs and small amounts of sulfate, metals nitrate, and other trace components [227]. The emissivity of motor vehicles and their performance can be improved in several ways, including by changing the type of fuel [23,29,226–228] or the power system [63,229–234] and recovering lost energy [176,187,211,217,235].

Biodiesel fuel is relatively easy to apply in diesel-powered motor vehicles. Biodiesel can be produced from local crops and waste, which allows for its greater availability and additionally gives an economic effect in the form of stimulating rural areas and sustainable development. The use of biodiesel brings certain benefits resulting from the reduction of PM and CO emissions. Unfortunately, you have to watch out for the increase in NOx and HC compared to pure diesel. Reduction of nitrogen oxides is possible through the use of selective catalytic reduction (SCR) systems in motor vehicles.

Currently, there are many trucks on the market, and manufacturers of marine engines offer a significant number of new CIEs equipped with a modern battery fuel system powered by pilot diesel and NG batches, such as Wartsila, MAN Diesel & Turbo and IVECO [63]. NG is a very promising and very attractive fuel due to its availability, extensive distribution infrastructure, low cost and clean combustion, which can be used as a transport fuel [97]. Conversion of the popular ICE to gaseous fuel leads primarily to the reduction of NOx and CO_2 emissions by 90–85% and 20–10%, respectively, and almost completely eliminates components such as PM and SO from exhaust gases [76]. These ecological properties in road transport are possible thanks to high-pressure (up to 2000–3000 bar) fuel injection systems, mainly of the common rail type in modern ICE.

The results showed that CNG had several advantages over diesel and petrol, including a significant reduction in emissions and costs [99]. Despite the good position of CNG on global transport markets, there are still many obstacles to their widespread use. The main obstacles to the use of CNG are as follows: problematic gas storage in the vehicle and loss of cargo space, vehicle refueling time, availability of refueling stations and supply problem in case of pipeline failure. Due to its lower energy density, NG, compared to petrol or diesel, takes up 3–4.5 times more storage space than petrol or diesel, which consequently reduces the range of the vehicle. In addition, this reduces the loading space of a vehicle, especially a passenger car or a small van, because additional gas tanks must be placed somewhere. This disadvantage can be eliminated by taking into account special additional gas tanks placed in the vehicle in the design process, but this applies only to newly designed vehicles. Refueling times for vehicles powered by natural gas are longer than for vehicles powered by conventional engines, and there may be a lack of refueling infrastructure in some places, especially on less frequented routes. This problem significantly limits the development of long-distance trucking on irregular routes. In addition, refueling a vehicle is considered the "least safe" moment of its use [99,236,237]. Therefore, based on the literature, it can be concluded that the use of natural gas as a transport fuel can contribute to improving air quality in cities, reducing the harmful health effects and social costs of atmospheric air pollution. Currently, alternative fuels are expected not to increase emissions and may provide comparable or even better engine performance [238,239].

There are various technologies such as Kinetic Energy Recovery Systems (KERS), Energy Harvesting Shock Absorber Systems (EHSA) and Waste Heat Recovery Units (WHRU) [240] for automotive energy recovery. Energy harvesting in self-powered systems is particularly needed not only as a sustainable and cost-effective alternative to conventional energy sources but also to help minimize the environmental impact of overuse of conventional energy resources [241].

Another widely discussed direction in the development of energy sources and drive sources for motor vehicles is undoubtedly electro mobility [64,119–128]. The use of EV is mainly supported by the lack of exhaust emissions at the place of use. However, the ecological aspects of EV should be looked much more widely. A comprehensive assessment of the impact of an EV on the natural environment should take into account not only the stage of use but also other stages occurring in the life cycle of the vehicle [64]. Thus, the life cycle of a vehicle consists of three main stages [64]:

- the production stage, which includes the extraction of the necessary raw materials, the production of the necessary materials and their transport;
- the vehicle operation stage;
- and the end-of-life vehicle management stage.

In the case of EV, the emission of pollution is a particularly important issue in the assessment of environmental risk during its operation. In this case, it is about the emission of substances from the production and distribution of electric energy used to charge the vehicle traction battery. Energy security in relation to EV consists in ensuring appropriate infrastructure in the form of charging points for EV that are able to generate and supply the traction batteries of vehicles with the appropriate amount of electricity [242]. Thus, the origin of the energy used during charging has an impact on the vehicle's emissions balance [10,64,242–245]. The improvement of the overall emissivity of EVs can be achieved by using RES for charging—for example, PV or wind energy. In the case of using solar energy, special sheds called carports are perfect; interesting research in this area is presented in [242]. However, emission issues are not the only problem about electric vehicles and electro mobility in the world. A big problem that does not convince drivers to buy EV is the limited range of the vehicle and the long battery charging time, which is from half an hour to several hours and even a day to fully charge. In addition, in many countries, there is no proper vehicle charging infrastructure [246], such as in Poland. The solution to these problems will certainly come with time; more and more efficient batteries are already appearing, and the charging infrastructure is developing. However, at the present time, it is still not enough to switch to EVs.

5. Conclusions

As shown in the review, alternative fuels to diesel oil and gasoline are of great interest, especially in developing countries with a large share of agriculture in the national economy. In addition, a large share of research work is visible in gaseous fuels (NG, CNG, LNG) in various transport applications, e.g., public transport vehicles or off-road vehicles and machines powered by an internal combustion engine. In many countries, such as Poland or the Netherlands, there is a large share of motor vehicles powered by an internal combustion engine running on LPG. It should be noted that in the case of fuels for internal combustion engines, no leader has yet emerged that could replace the existing fossil fuels with such a large share as them. Here, there is still a significant cost of generating and storing energy in fuel, which should be settled within a few years due to technological development in the field of energy storage. In the coming years, more and more attention will be paid to hydrogen fuels, and ammonia will be an equally interesting research direction. The development of electro mobility will also be of great importance, with many countries seeing significant progress in this technology.

Another issue that is possible regardless of the type of power supply for the ICE in the vehicle is the possibility of recovering energy lost using energy harvesting systems. This direction is strongly developed and brings great benefits with relatively small expenditures and small modifications. An additional advantage of these systems is their progressive miniaturization. As shown in the review, the average energy yield in passenger cars is up to 300 W, and in the case of larger vehicles, the benefits are greater.

To sum up, it can be said that the best energy effects are achieved by a hybrid system, i.e., the use of alternative fuels and the use of energy collection devices in vehicles powered by ICE. In the case of electric vehicles, good effects are obtained by using energy management during vehicle braking. The undisputed leader in terms of universality of use are energy recovery systems from the vehicle suspension system, due to the fact that each vehicle, regardless of the drive source, has a suspension system responsible for driving comfort and vehicle safety in motion.

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Abbreviations

EU	European Union
FAME	Fatty Acid Methyl Esters
RES	Renewable Energy Sources
NG	Natural Gas
CNG	Compressed Natural Gas
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
SSF	Simultaneous Saccharification and Fermentation
AD	Anaerobic Digestion
L-AD	Liquid Anaerobic Digestion
D-AD	Dry Anaerobic Digestion
ATEGs	Automotive Thermoelectric Generators
TEM	Thermoelectric generator modules
TEG	Thermoelectric generator
ICE	Internal Combustion Engines
ETEG	Exhaust-Based Thermoelectric Generator
CFD	Computational Fluid Dynamics
WHTC	World Harmonized Transition Cycle
SUV	Sports Utility Vehicle
DOC	Diesel Oxidation Catalytic Converter
LVGs	Longitudinal Vortex Generators
WLTC	World Light Vehicle Test Cycle
PMSM	Permanent Magnet Synchronous Motor
CVT	Continuously Variable Transmission
ISG	Integrated Starter Generator
CAN	Controller Area Network
UCs	Ultra-Capacitors
KERS	Kinetic Energy Recovery System
EV	Electric Vehicle
B	class of the road
C	class of the road
F	force
v_1	vehicle body velocities
v_2	chassis velocities
b	inertia value
c_{eq}	equivalent damping coefficient
EHSA	Energy Harvesting Shock Absorber
WHRU	Waste Heat Recovery Units
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane

HC	Hydrocarbons
HHO	Hydrogen and Oxygen
NOx	Nitrogen Oxides
PAHs	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PM	Particulate Mater
RBE	Rapeseed Oil Butyl Esters
RID	International Carriage of Dangerous Goods by Rail
RME	Rapeseed Oil Methyl Esters
SO_2	Sulphur dioxide

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