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Review

Overview of the Potential of Energy Harvesting Sources in Electric Vehicles

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Abstract: Energy harvesting, a cutting-edge technology that captures wasted energy from vehicles, constitutes a means to improve the efficiency of electric vehicles. Dissipated energy can be converted into electricity using regenerative energy recovery systems and put to various uses. This study tenders a thorough examination into energy recovery technologies which could be applied to the various types of energy dissipated in electric vehicles. The paper investigates the possible sources of energy recoverable from an electric vehicle, as well as the various types of energy dissipated. It also examines the energy recovery technologies most frequently used in vehicles, categorizing them according to the type of energy and application. Finally, it determines that with further research and development, energy harvesting holds considerable potential for improving the energy efficiency of electric vehicles. New and innovative methods for capturing and utilizing wasted energy in electric vehicles can be established. The potential benefit of applying energy recovery systems in electric vehicles is a vital issue for the automobile industry to focus on due to the potential benefits involved. The ongoing progress currently being made in this field is expected to play a significant role in shaping the future of transportation.

Keywords: electric vehicle; energy harvesting; thermal energy; mechanical energy

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1. Introduction

The process of collecting energy from different sources and using it to power electronic devices is known as energy harvesting. In the setting of electric vehicles (EVs), energy harvesting sources can supplement the main battery to extend the distance a vehicle can cover. There are several possible energy sources that an EV can harvest, including [1,2]:

- Regenerative braking, suspension, and rolling energy generated during braking can be captured and stored in the vehicle's battery.
- Kinetic energy recovery: energy from the motion of the vehicle which can be captured and stored.
- Waste heat recovery: energy from the heat generated by the vehicle powertrain and other systems which can be captured and reused to generate power.

Overall, energy harvesting sources can help to improve EV efficiency and reduce reliance on the primary battery, resulting in an increased range of distance and a reduced impact on the environment [3,4]. The electrification of powertrains is one of the cutting-edge technologies used in the automotive industry to mitigate pollution resulting from greenhouse gas emissions from vehicles in transportation. However, further and deeper study is required to improve fuel efficiency in these kinds of vehicles. The ability to recover the energy expended, whether from a thermal, vibratory, or other type of source fueling an electric car, would be a valuable and innovative addition to this field of study. When circulating in towns, electric vehicles use 83% of the energy supplied by the battery for propulsion, with 21% lost in aerodynamics, 18% lost in rolling resistance, and 27% lost during braking. On highways, these vehicles use 87% of battery power, with 45% lost in aerodynamics, 22% lost in rolling resistance, and 7% lost during braking [5]. The energy recovery systems that are employed in the automotive sector are methods for recovering energy from the vehicle that would otherwise be wasted. The recovered energy can be stored and then used again as required, thus reducing the need for an alternative energy source and hence improving vehicle efficiency. These systems can operate for a broad range of technologies present in automotive powertrains [6]. The automotive business has traditionally concentrated on more conventional ways of improving vehicle fuel efficiency such as engine efficiency or aerodynamics. Manufacturers have only recently recognized that these recovery systems offer a cost-effective alternative for improving efficiency, and as a result these systems are now being developed.

Electric vehicle engines differ from combustion engines in a number of ways. Electric vehicles are powered by the electricity stored in their batteries and consequently do not release greenhouse gas emissions. They are also more energy efficient and have lower operating costs. They provide immediate rotational force (torque) which enables rapid acceleration. However, combustion powered vehicles generally boast a longer driving range and are faster to refuel. Electrically powered vehicles are silent and foster the use of renewable energy sources. The infrastructure providing charging facilities for these vehicles now requires expansion.

Energy harvesting in electric vehicles enables the recovery and reuse of otherwise wasted energy, effectively extending the vehicle range. This feature proves particularly advantageous in situations such as stop-and-go traffic or during deceleration and braking. By harnessing and utilizing this typically lost energy, electric cars significantly enhance their energy efficiency, which results in reduced overall energy consumption. Consequently, the reliance on external power sources is reduced, and sustainable transportation is achieved. The integration of renewable energy sources, such as regenerative braking and solar panels, mounted within the vehicle itself, further contributes to minimizing harmful environmental impact.

Moreover, energy harvesting offers cost savings for electric vehicle owners. By reusing energy that would otherwise go to waste, there is less dependency on the external charging infrastructure. This reduction can potentially lower electricity costs and decrease the frequency of charging requirements. Additionally, energy harvesting systems alleviate the strain on the battery by supplementing vehicle energy needs. This not only helps extend battery lifespan but also reduces the frequency of battery replacements, thus resulting in long-term cost savings.

Electric vehicles can harvest energy from diverse sources such as braking, ground–wheel interaction, and aerodynamics. This range of energy sources provides a wide selection of options for energy recovery and makes electric cars adaptable and efficient across various driving conditions.

This article aims to provide an overview of the potential sources for harvesting energy and the recovery technologies appropriate for each type of energy. It will classify each source based on the type and amount of energy available, the target application, methods, applicable technologies, and efficiency. The purpose is to give the reader a comprehensive understanding of the energy harvesting landscape, an overview of the possible energy harvesting sources, as well as the recovery technologies for each form of energy. Each source will be classified according to the type and amount of energy accessible, the intended application, methods, applicable technologies, and efficiency.

The whole paper is organized as described in the methodology section. After the three sections of introduction, related works and methodology, Section 4 focuses on the possible energy sources available to glean in an electric vehicle. Section 5 reports the various systems and technologies that are appropriate for recovering each form or source of energy. Section 6 relates to the use of recovered energy and investigates the different ways in which it can be used to power various applications. Finally, technical challenges and future work and conclusions are presented in Sections 7 and 8.

2. Related Works

A great variety of sectors can benefit from energy recovery practices, not least the automotive industry. Most studies on energy harvesting focus only on a single aspect of energy generation.

The authors in [7] specifically examine how energy can be recovered from shock absorbers. The significance of regenerative dampers is emphasized, and an assessment is made of the potential for recovery methods for energy generated by automotive vibration. The different types of regenerative shock absorbers are then categorized and summarized. The technologies employed in regenerative shock absorber systems are categorized and evaluated in [8]. The article reviews three modes of operation for these systems: direct drive, indirect drive, and hybrid drive, and assesses the feasibility for implementation of each type. The aim of the study is to analyze the performance of regenerative shock absorbers by subjecting vehicle suspension systems to various types of road excitations. The results in [9] indicate that there is significant promise for energy recovery from automobile suspension vibration with hydraulic and electrical regenerative structures showing exceptional performance and exhibiting significant growth potential. The authors of [10] examine vehicle energy dispersal and the potential for recovering that energy by using a regenerative shock absorber, and also review various innovative works regarding energy recovery across all sectors. The authors of [11] provide an overview of the different energy harvesting techniques used in roads and bridges, such as photovoltaic cells, solar collectors, geothermal, thermoelectric, electromagnetic, and piezoelectric systems. The harvested energy can be used to produce electricity, heat or cool buildings, melt ice, power wireless sensors, and monitor structure conditions. The research compares different energy harvesting technologies taking into consideration power output, cost-effectiveness, technology readiness level, benefits, and drawbacks. The authors of [12] provide a thorough examination of roadway energy harvesting technologies, including the harvesting principle, prototype development, implementation efforts, and economic factors of each technology. According to the research, several of these technologies are advanced enough to generate electrical power on their own at the roadside. Ref. [13] examines various energy harvesting concepts for the railway industry, both on-board and wayside, classifying harvesters by the source of energy harvested and critically analyzing the benefits and drawbacks of each type. The review identifies the most promising energy harvesting solutions and advocates for additional research in this field. Ref. [14] examines energy harvesting technologies for various land transportation uses, showing various energy harvesting systems in terms of design, simulation, and experimentation. The authors of [6] concentrate on the technical aspects of energy recovery systems and their potential to reduce carbon emissions. Energy recovery systems are classified here based on the energy sources and methods used to harvest and store it. A critical assessment of factors such as weight, size, and cost are carried out, but the emphasis is on vehicles powered by internal combustion engines.

3. Methodology

Figure 1 depicts the flowchart approach used in this study. There is a summary of the studies and other contributions related to energy harvesting in electric cars which emphasizes the contribution made by the review. Possible sources of energy harvesting in electric vehicles, as well as the different kinds of energies and technologies for harvesting them, are also discussed. There is a growing interest in this topic due to its importance to the automotive industry and the need for new avenues to reduce environmental impact. This has led to an increased focus on further research in this area. This study also includes several applications for recovered energy and deals with the challenges associated with implementing the solutions suggested in this field.

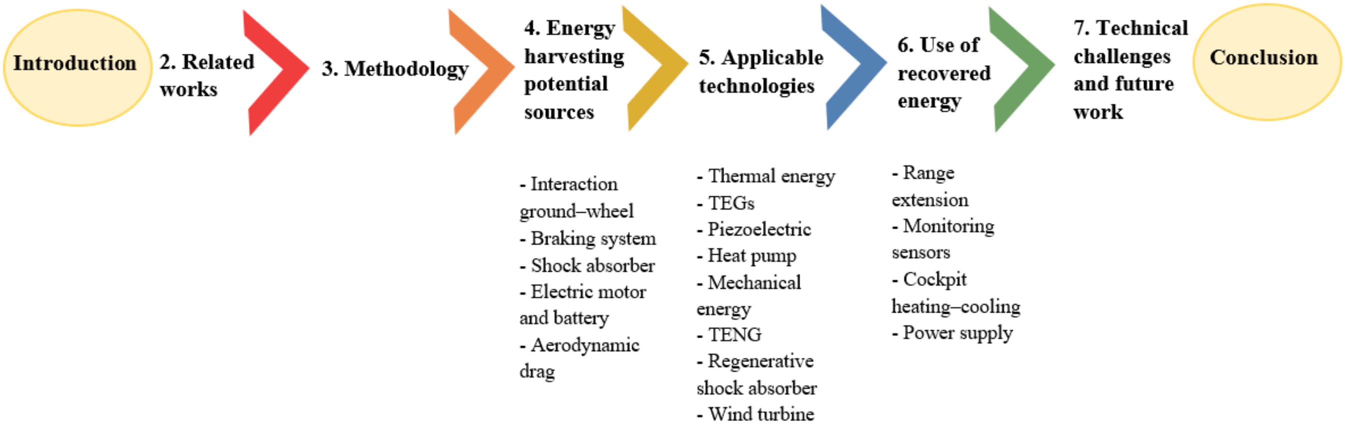

Figure 1. The flowchart of this research.

4. Potential Energy Sources

In an electric vehicle, energy is stored in the battery, which functions as the vehicle's primary power source (Figure 2). The battery is used to power the electric motor, which drives the wheels and propels the car forward [15]. However, some of the energy stored in the battery is dissipated or lost in various sections of the vehicle due to thermal or vibrational causes. These losses can be collected and recycled as alternative energy sources, increasing the total efficiency of the electric vehicle. The interaction between the ground and the wheel, the braking system, the shock absorber, the electric motor and battery, and the aerodynamic drag are all possible sources for energy recovery. These energy sources are depicted in a diagram that illustrates the flow of energy from the battery used in an electric car. The aim of energy recovery is to convert these losses into usable energy that can then be reused to power the vehicle or stored in the battery for later use.

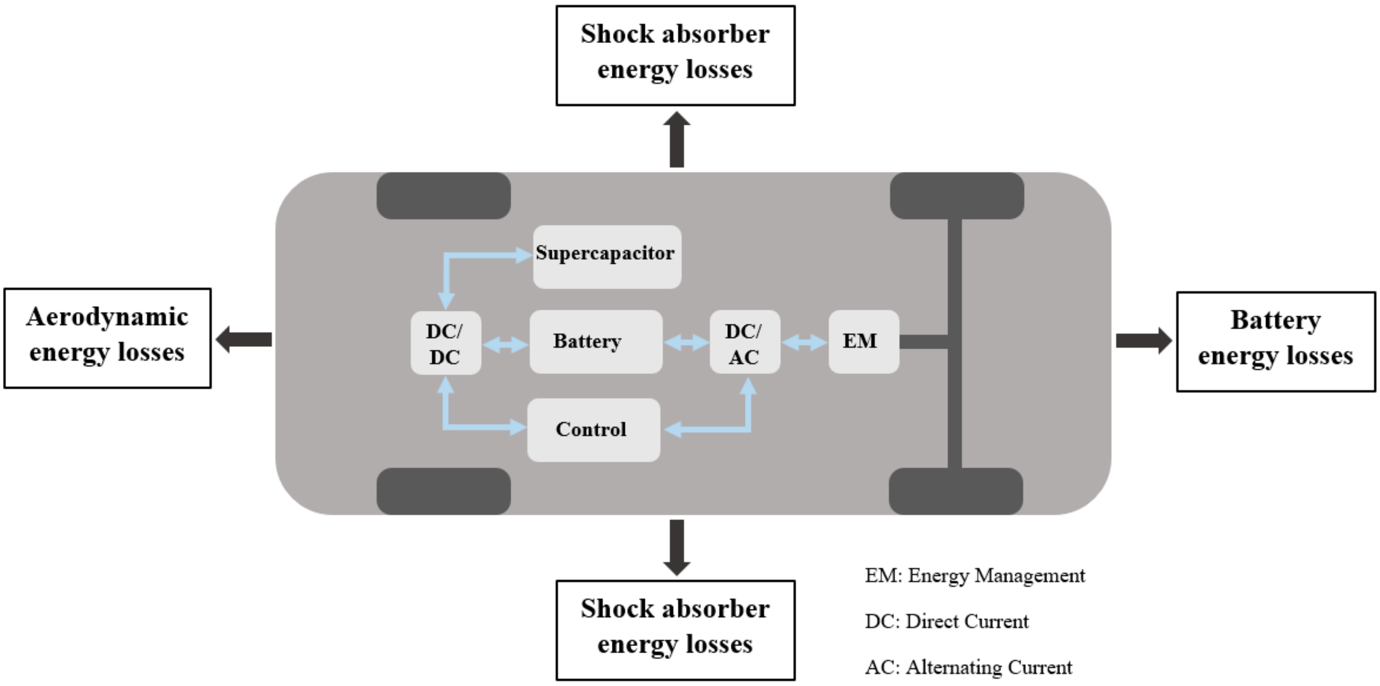

Figure 2. Energy flow in electric vehicle.

Energy flows from the battery to the electric motor, which then converts this electrical energy into mechanical energy to drive the wheels in an electric car. The electric motor is driven by an inverter, which converts the direct current (DC) from the battery to the alternating current (AC) required by the motor. When the vehicle is braking or coasting, the electric engine can function as a generator, converting some of the vehicle's kinetic energy back into electrical energy. This energy is then stored in the battery and used to power the engine later. Furthermore, the vehicle may have auxiliary systems that require electrical energy to function, such as air conditioning or heating. This energy is derived from the battery as well. In summary, energy flows from the battery to the electric motor in an electric car, with energy captured during braking or coasting and used to recharge the battery.

4.1. Interaction Ground–Wheel

In a vehicle, the interaction between the ground and the wheel creates a major source of energy loss. Rolling resistance is the force that resists the direction of movement the tire makes on the traction surface during this interaction. Rolling resistance is caused by deformation in the tire when it comes into contact with the ground, and results in a loss of mechanical energy. Fortunately, using suitable technologies, this energy can be captured and transformed into a new source of energy and adding to efficiency. The tire, as the final component of the driveline, is critical in this respect [16]. The study of mechanical energy loss through contact has been a topic of interest for researchers, who aim to find ways to harness this energy for practical use [17].

4.2. Braking System

Various studies [18] have recorded the conversion of kinetic energy into thermal energy caused by the friction between the brake disc and pads during the braking process. These studies have recorded a wide range of braking temperatures, with temperatures as low as 150 °C reported in works such as [19,20]. Temperatures between 150 °C and 300 °C have been measured by others, including [21–26], while temperatures above 300 °C have been documented by [27–30]. Furthermore, braking can cause triboelectrification, which provides another possible source of recoverable energy [31]. As a result, the energy recovered from the braking mechanism can be divided into two types: thermal energy and triboelectric energy.

4.3. Shock Absorber

Another form of energy loss in a vehicle that can be recovered is that of the shock absorber. The shock absorber is critical in delivering a comfortable ride and maintaining vehicle stability. It absorbs road bumps and vibrations, reducing the discomfort for passengers and wear on vehicle components. Because of its internal hydraulic resistance, the shock absorber transforms kinetic energy into heat energy. This heat energy can be recovered and converted into power. Through the piezoelectric effect, the shock absorber can also be used as a power source. The piezoelectric effect is the generation of an electric charge because of mechanical tension exerted on certain materials. As a result, the shock absorber can be integrated into a vehicle as a piezoelectric energy harvester. The car suspension facilitates the transmission of force and torque between the vehicle body and wheels. The automobile suspension, a key component that supports both the vehicle body and the wheels, helps to mitigate the impact caused by uneven road surfaces and guarantees a pleasant driving experience in the vehicle body [32]. Both the tires and the vehicle suspension usually absorb vibrational energy, though the tires only absorb a small amount due to their limited damping ability. The suspension absorbs and dissipates the main amount of vibrational energy [33].

4.4. Electric Motor and Battery

The main source of power in an electric vehicle is the electric motor. The motor converts the electrical energy from the battery into mechanical energy that propels the car. However, this process is not completely efficient, and some of the electrical energy from the battery is wasted as heat or sound. Furthermore, the battery suffers energy losses due to internal resistance and temperature changes, which impact the capacity. Consequently, the losses from an electric vehicle motor and battery are potential sources of energy that can be recovered and used for other purposes. The heat produced by the battery and electric motor can be used as a source of thermal energy. Several investigations have shown that these components contain heat. Battery temperatures below 40 °C have been reported in references [34–41]. Meanwhile, studies such as [42–49] measured temperatures ranging from 40 °C to 60 °C, with [50,51] recording temperatures higher than 60 °C. Temperature changes in electric motors can be classified into three groups: less than 50 °C, as seen in [52], between 50 °C and 100 °C, as seen in [53–59] and above 100 °C, as seen in [60–65]. In ref [59], both theoretical modeling and experimental investigations of the latest thermal management methods are reviewed. Table 1 summarizes the classification of available energy sources according to various criteria. The reviews state that operating temperatures of Li-ion batteries typically range from −20 °C to 60 °C, with an ideal range of 20 °C to 40 °C for optimal performance and lifespan. The authors also note that temperature management is critical for preventing thermal runaway and ensuring safe operation of the battery system. Overall, the review supports the idea that careful temperature management is essential for the optimal performance, safety, and lifespan of electric vehicle batteries, and highlights the importance of ongoing research and innovation in battery thermal management to improve the efficiency and sustainability of electric vehicles.

Table 1. Classification of available energy sources according to energy source, value of available energy, type of energy, experimental/simulation, and targeted application.

References	Sources	Temperature or Amount of Energy Available	Energy Type	Experimental/ Simulation	Targeted Application
[17]	Ground–wheel interaction		Vibration energy	Simulation	Energy harvesting
[66]	Ground–wheel interaction		Vibration energy	Experimental	Energy harvesting
[67]	Ground–wheel interaction		Vibration energy	Simulation and experimental	Energy harvesting
[68,69]	Aerodynamic drag		Vibration energy	Simulation	Energy harvesting
[70]	Aerodynamic drag		Vibration energy	Simulation and experimental	Energy harvesting
[71–74]	Shock absorber		Vibration energy	Experimental	Energy harvesting
[75]	Shock absorber		Vibration energy	Simulation	Energy harvesting
[76,77]	Braking system	[30 °C; 300 °C]	Thermal energy	Simulation	Energy harvesting
[31]	Braking system		Vibration energy	Experimental	Energy harvesting
[34,35]	Battery	<40 °C	Thermal energy	Experimental	Energy management
[36,41]	Battery	<40 °C	Thermal energy	Simulation	Energy management
[42]	Battery	[40 °C; 60 °C]	Thermal energy	Simulation	Energy management and harvesting
[43]	Battery	[40 °C; 60 °C]	Thermal energy	Experimental	Energy management and harvesting
[50]	Battery	>60 °C	Thermal energy	Simulation	Energy management and harvesting
[51]	Battery	>60 °C	Thermal energy	Experimental	Energy management and harvesting
[52]	Electric motor	<50 °C	Thermal energy	Simulation	Energy management and harvesting
[53]	Electric motor	[50 °C; 100 °C]	Thermal energy	Simulation	Energy management
[54]	Electric motor	[50 °C; 100 °C]	Thermal energy	Experimental	Energy management
[60,61]	Electric motor	>100 °C	Thermal energy	Simulation	Energy management

4.5. Aerodynamic Drag Source

Aerodynamic drag is the resistance to motion produced by the air that surrounds a vehicle. It is a significant contributor to vehicle fuel usage and is caused by the interaction between the vehicle and the air it moves through. Aerodynamic drag can be decreased by streamlining the vehicle shape, reducing its frontal area, and optimizing its body design to minimize airflow turbulence. This reduction in drag results in less energy loss, which leads to lower fuel usage and lower emissions. Engineers can optimize the aerodynamic drag of a vehicle to reduce its effect on fuel consumption by controlling the airflow over the vehicle surface and through the underbody.

Aerodynamic drag happens when a vehicle is in motion and encounters resistance from the air relative to its speed. This opposing force, which causes a loss of momentum, can significantly affect vehicle fuel consumption and emissions. To offset this, aerodynamic drag can be reduced or captured [63]. Recovering and utilizing this dynamic energy would be an asset for improving the total energy efficiency in an electric vehicle.

5. Applicable Technologies

Figure 3 shows the two major forms of energy that can be recovered from an electric vehicle: thermal energy and mechanical energy. There are specific technologies available to successfully recover these sources of energy, which have different levels of efficiency and have undergone simulation or experimental testing. Table 2 categorizes the various sources of recoverable energy and the technologies most appropriate for capturing them based on the efficiency and the method applied.

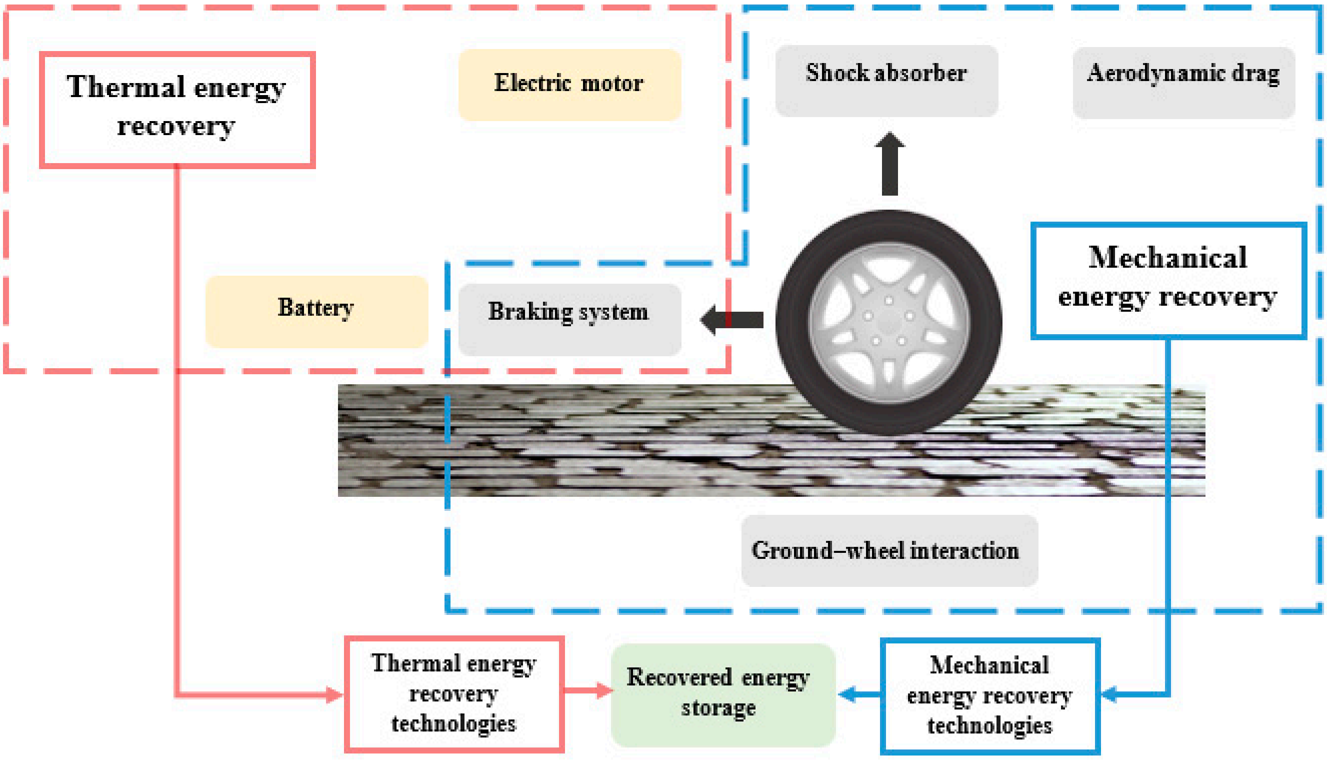

Figure 3. Type of energy recoverable with processes of recovery.

5.1. Thermal Energy Recovery

Heat is produced as a by-product by various processes taking place in an electric vehicle, such as braking, battery, and motor operations. It is captured by means of thermal energy recovery. This heat energy can used to enhance the vehicle overall energy efficiency. The most suitable technology for capturing and utilizing this thermal energy is determined by the process efficiency and whether it is applied through simulation or experiment. Thermal energy recovery technologies used in electric cars include thermoelectric generators, waste heat recovery systems, and heat pumps. With the help of a heat pump, the recovered thermal energy can also be used to heat the passenger compartment, offering a more comfortable experience for passengers.

5.2. Thermoelectric Generator Module (TEG)

The thermoelectric generator (TEG) module is a device that uses thermoelectric effects to transform heat energy into electrical energy. TEGs can be used in electric vehicles to capture and convert waste heat escaping from the vehicle into usable electricity. This waste heat is generated by the battery, the electric motor, and the braking system. The reconverted energy can then be used to power the car or be stored for later use. TEGs have been studied and used in different projects where they demonstrated their potential for increasing the total energy efficiency of electric vehicles. TEGs are made up of a succession of thermoelectric modules that are sandwiched between two heat exchangers. Figure 4 shows a TEG module type used in [78]. However, typical thermoelectric devices show low thermoelectric conversion efficiency at low temperatures and easy thermal equilibration. A thermo-magneto-pyroelectric energy generator (TMPyEG), which is a combination of a thermo-magneto-electric generator and a pyroelectric generator, was developed to continuously harvest waste heat and convert it into electric output [79].

Figure 4. Model of a thermoelectric generator module [79].

Thermoelectric generator modules (TEGs) are often used to recover some of the thermal energy lost from a source. Research has been carried out into the use of TEGs in the automotive industry, specifically for the purpose of enhancing energy efficiency and decreasing emissions. Investigations such as [6,79] propose TEGs for installation onto the exhaust system of an internal combustion engine vehicle. Another study [80] suggests installing TEGs on both the exhaust and the motor of an internal combustion engine vehicle. Additionally, a simulation study presented in [21] examines the potential for TEGs to recover the heat lost during braking when the brake pads come into contact with the disc.

5.3. Piezoelectric Transducer

Piezoelectric transducers transform mechanical energy into electrical energy and vice versa. They operate by the piezoelectric effect, which states that when certain materials are subjected to varying amounts of mechanical stress, an electrical charge is generated. Piezoelectric transducers can be used to recover vehicle waste energy recovery and to convert vibrational energy from the vehicle into electrical energy.

Piezoelectric transducers have been widely investigated for energy harvesting applications in automobiles. The authors of [81] employed a dynamical model which used the device modes to identify the optimal potential for harvesting energy. The model identified the vibrational frequencies of the energy harvested. The relationship between flexure and pressure has also been studied in [82] to assess the performance of a ceramic piezoelectric harvester for use in vehicles. The authors of [83] conducted research to determine the best locations for harvesting energy from a vehicle with piezoelectric devices. The authors in [70] used wind pressure and vibrations occurring during driving to generate electricity to power microsensors on the vehicle. Furthermore, as demonstrated in [74,75], piezoelectric technology could be used to recover waste energy from the vertical movement of the vehicle shock absorbers.

5.4. Heat Pump (HP) and Positive Temperature Coefficient (PTC)

Heat pump and PTC (Positive Temperature Coefficient) are two different technologies used in electrical vehicles (EVs) for managing thermal comfort and optimizing energy efficiency. A heat pump in an EV is a system that can provide both heating and cooling by transferring heat between the inside and outside of the vehicle. It utilizes the principles of refrigeration to extract heat from the ambient air or the vehicle's surroundings and delivers it into the cabin when heating is required. Any excess heat from the battery and electrical systems, plus air outside the car, is compressed at high pressure. This compression raises the temperature, which can then be used to heat the cabin. In cooling mode, the heat pump removes heat from the cabin and releases it outside, providing air conditioning. This technology is more energy efficient compared to conventional resistive heating or cooling systems, as it transfers heat instead of generating it. A heat pump can also help improve the energy efficiency of an electric vehicle, reduce emissions, and increase passenger comfort by capturing and reusing the thermal energy produced by the vehicle. This in itself can increase the range of autonomy [84]. The authors in [85] review the electric vehicle range extension strategies based on an improved AC system in a cold climate. Furthermore, ref. [86] suggests an electric vehicle thermal management where the operation cost per hundred kilometers for heating mode is decreased by 20.83% compared with that of positive temperature coefficient heaters.

Positive Temperature Coefficient (PTC) is a heating technology used in EVs, typically employed for rapid cabin heating during cold weather [87]. PTC heaters consist of heating elements made of a ceramic material with a positive temperature coefficient. When an electrical current passes through these elements, their resistance increases as the temperature rises. This self-regulating characteristic ensures that the heating elements do not overheat. PTC heaters are known for their quick response and ability to provide near-instantaneous heat [88].

To reduce the consumption of energy required for heating, ref. [35] proposes a phased control technique for multi-source distributed heat. This method employs a variety of heat sources to gradually warm the car. These include battery waste heat cooling, engine waste heat cooling, and heat pump air conditioning. The authors of [89] concluded that heat pump scenarios lead to 41–72% lower energy consumption than that of a PTC when evaluating cabin heating energy consumption and driving range for a battery electric vehicle.

5.5. Mechanical Energy Recovery

Mechanical energy recovery is the conversion of kinetic energy, lost during an object's motion, into another type of energy that can be reused. This refers to the conversion of kinetic energy, lost during braking, into electrical energy that can be stored in the vehicle battery in electric cars. Regenerative braking systems, flywheel energy storage systems, and hydraulic energy recovery systems are some of the technologies available for recovering mechanical energy from an electric vehicle. These systems are intended to convert braking energy into electrical energy, which can then be stored and reused to power the vehicle.

5.6. Triboelectric Nanogenerator (TENG)

The triboelectric nanogenerator (TENG) is a cutting-edge energy harvesting device that converts mechanical energy into electricity by harnessing the power by the triboelectric effect. This concept is based on the interaction of two materials with opposing electrostatic properties. TENGs have received a lot of attention due to their ability to gather energy from a variety of sources including human motion and environmental energy. TENGs have been suggested for use in a variety of applications, including wearable devices, sensors, and energy harvesting systems [66,90]. In the automotive sector, studies such as [17,66] investigated the use of TENGs to recover energy from wheel rotation. These plans differ in structure, design, and location, with some TENGs placed inside the wheel and others on the outside of it, as illustrated in Figure 5.

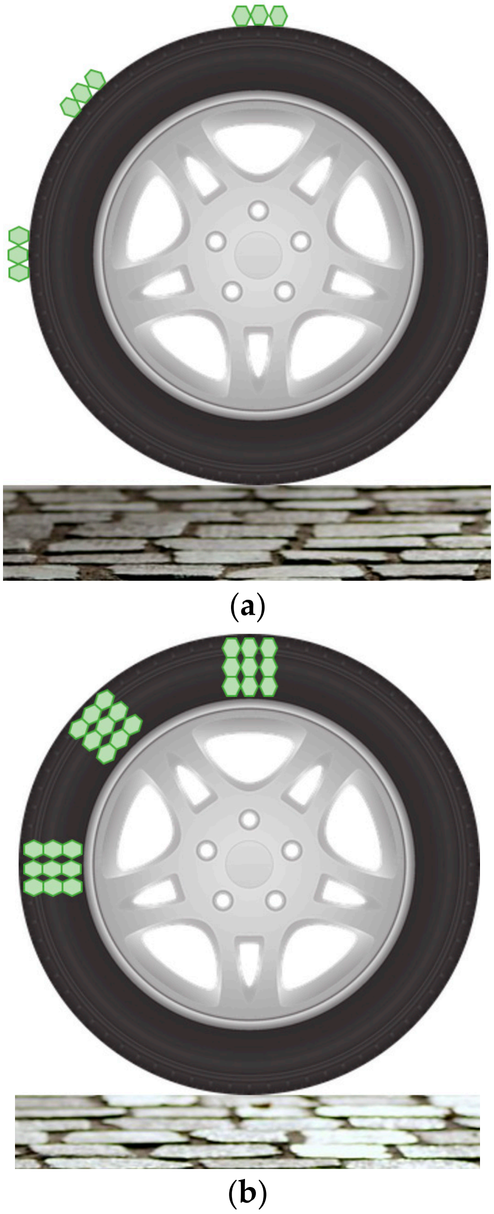

Figure 5. TENGs installed: (**a**) outside the tires, (**b**) inside the tires.

Several studies, including [31], have used the triboelectric nanogenerator (TENG) to recover waste energy during braking. The research suggests using a disc-shaped TENG that is subjected to pressure during braking when the brake pads make contact with the rotating disc.

5.7. Regenerative Shock Absorber

A regenerative shock absorber is a form of shock absorber that converts energy from vehicle oscillation into electrical energy. This mechanism converts mechanical energy from the suspension system into electrical energy via a generator, such as a linear alternator. The recovered energy can then be used to power different vehicle systems or be stored in a battery. To increase the energy efficiency of electric vehicles, researchers have suggested using regenerative shock absorbers. Vehicle suspension vibrations can be used to recover energy. The waste energy recovery potential of typical passenger vehicle suspensions ranges from 100 W to 400 W, indicating a large potential for energy recovery. This potential is proportional to the intensity of the vibrations, with stronger vibrations implying a higher potential [14]. Regenerative shock absorber systems come in a variety of configurations and include hydraulic and mechanical systems. A mechanical–electromagnetic–hydraulic coupling system is one suggested system, and includes components such as a hydraulic cylinder, non-return valve, accumulator, hydraulic motor, generator, and pipeline [71]. The system operates by converting external excitation energy into electrical energy via an energy conversion mechanism. When the pistons of the hydraulic cylinder are driven toward each other by external excitation, the oil flows through the valve system for rectification and then through the accumulator to weaken the fluctuations. This results in a constant flow of oil to drive the hydraulic motor and generate electricity (Figure 6) [71].

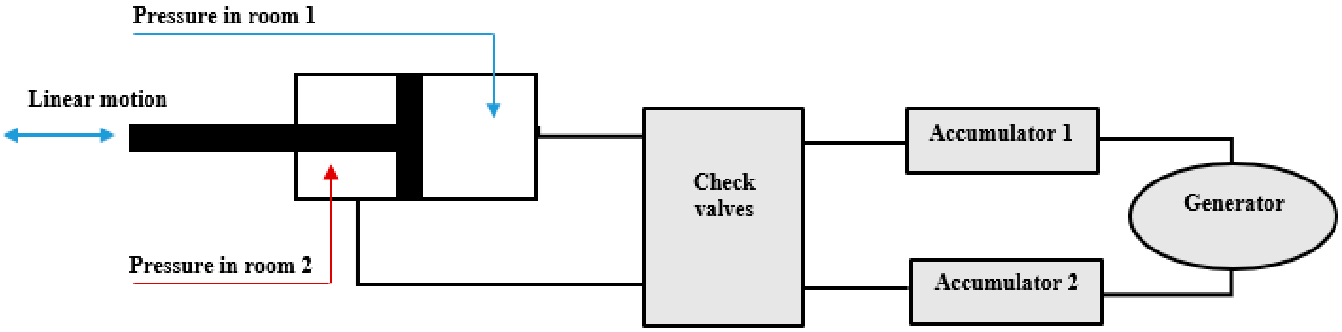

Figure 6. The working principle of energy regenerative electromagnetic hydraulic shock absorber (Image adapted from [71]).

The research in [72] concentrated on a mechanical type of regenerative shock absorber that seeks to improve autonomy in electric vehicles. The design employs a double ball screw transmission to provide propulsion, rather than a hydraulic cylinder piston, similar to [71].

5.8. Wind Turbine

Wind turbines can be used to produce electricity for electric cars. They can transform mechanical energy into electrical energy, which can then be used to power electric vehicles. Energy generated by wind turbines is used for electric vehicles to increase range and decrease reliance on grid energy. Wind turbine energy harvesting can provide enough energy to completely power an electric car in certain cases, enabling it to run on clean, renewable energy. The incorporation of wind turbines into electric vehicles holds promise as an anticipated development in the effort to attain environmentally friendly, sustainable transportation solutions.

Different wind turbine installations are suggested for harvesting wind energy in [68,69]. The power generation process is depicted in Figure 7 with a wind turbine model, which converts wind power into electrical energy via a small wind power generator and an air duct.

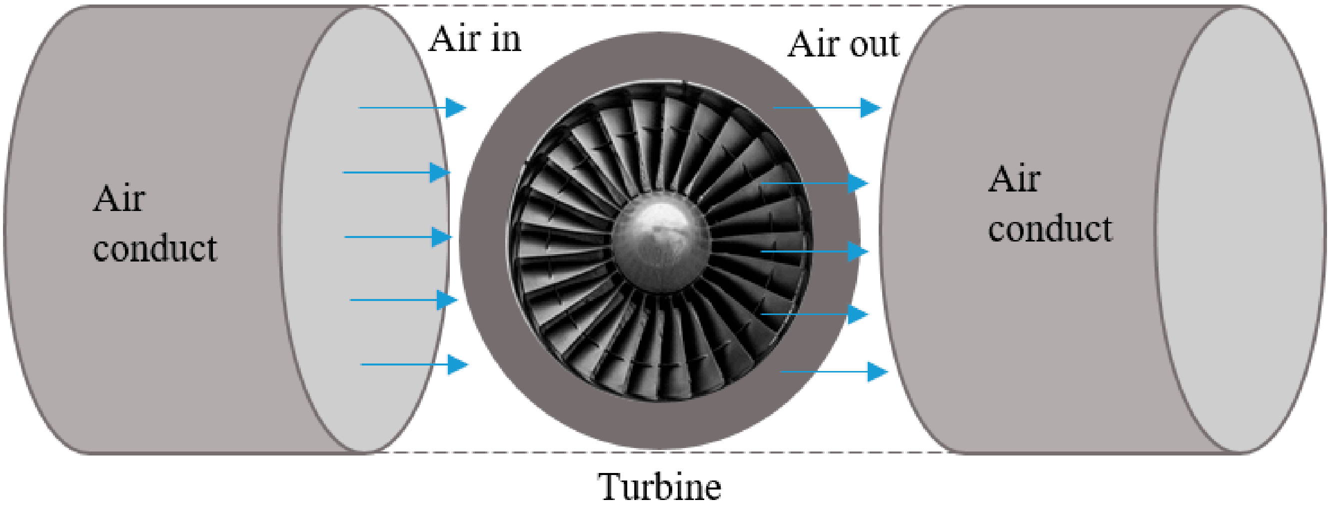

Figure 7. Diagram of the wind energy recovery system in an air duct.

Table 2 classifies suitable technologies for different types of energy by considering several criteria. These include the energy source, the type of energy to be retrieved, the harvesting methods, efficiency measures, and whether the technology has undergone experimentation or simulation. Table 3 provides the results of a comprehensive examination of the advantages and disadvantages associated with each recovery technology.

Table 2. Classification of suitable technologies for each type of energy according to the energy source, the type of energy to be recovered, harvesting technologies, the efficiency measure, and experimental/simulation.

References	Sources	Type of Energy	Harvesting Technologies	Efficiency Measurement	Experimental/Simulation
[17]	Ground–wheel interaction	Vibration	Triboelectric nanogenerator	• P_{max} = 1.9 mW per unit • P_{max} = 1.2 W/500 units	Simulation
[66]	Ground–wheel interaction	Vibration	Triboelectric nanogenerator	• P_{max} = 1.79 mW	Experimental
[67]	Ground–wheel interaction	Vibration	Triboelectric nanogenerator	• P = 0.5 mW	Simulation and experimental
[68,69]	Aerodynamic drag	Vibration	Wind turbine	• 7.32% C Efficiency < 7.71%	Simulation
[70]	Aerodynamic drag	Vibration	Piezoelectric transducer	• P_{max} = 31.8 mW per unit • $P_{average}$ = 14.5 W/500 units	Simulation and experimental
[74]	Shock absorber	Vibration	Piezoelectric transducer	• 0.001 W < P < 0.07 W	Simulation
[72]	Shock absorber	Vibration	Mechanical type shock absorber	• Eff_{max} = 51.1%	Experimental
[73]	Shock absorber	Vibration	Linear motor type shock absorber	• Eff_{max} = 52%	Experimental
[76]	Braking system	Thermal	Pyroelectric material PZT	• 2.0 V < U_{out} < 5.2 V	Simulation
[87]	Braking system	Electromagnetic	Faraday disc		Simulation
[77]	Braking system	Thermal	Thermoelectric generator	• 0.0129 V < U_{out} < 28.64 V	Simulation
[31]	Braking system	Vibration	Triboelectric nanogenerator	• 0.65 V < U_{out} < 5.4 V	Experimental

Table 3. Advantages and disadvantages of each recovery technology.

Technology	Disadvantages	Advantages
TEG	Low output performance Conversion efficiency low	Continuous energy recuperation Faster engine warm-up
Heat pump and PTC	Performance dependence on outdoor temperatures and the need for additional heating in very cold weather	Rapid heating and low energy consumption
Piezoelectric	Transducer array and high cost for high energy output	Use for both energy harvesting and sensors
Wind turbine	Installation in the vehicle and dependent on topography, weather, and environment	No power source required and does not degrade air quality
Regenerative shock absorber	Easy to retrofit and no space or significant weight added	Best results for heavy and off-road vehicles
TENG	Low durability High frictional damage	High efficiency at low frequency; low cost, low density, light weight

6. Use of Recovered Energy

Energy recovery is the conversion of energy losses that occur at different stages in systems powered by an energy source into the form of energy that is available through specially designed devices and can be reused when required [91]. The recovered energy can then be used to increase range, charge various electrical devices such as sensors/instruments, or serve as an alternative heat source in the cockpit (Figure 8). The following are some typical applications for recovered energy:

- Increasing car kilometric range: Recovered energy can be used to extend the range of electric vehicles. This is especially helpful when the battery power is low and a boost is required.
- Battery recharge: The recovered energy can be used to fill the electric vehicle battery. This increases not only the range but also the battery lifespan.
- Improving car performance: The recovered energy can also be used to boost the performance of an electric vehicle. This involves boosting acceleration power and increasing maximum speed as well as reducing vehicle weight.
- Powering accessories: Recovered energy can power different electric car accessories such as the air conditioning system, lighting, embedded sensors [81–83], and infotainment systems.
- Fuel efficiency: The recovered energy can be used to enhance the vehicle's fuel efficiency. The use of fossil fuels is reduced by using recovered energy to power the car, resulting in lower emissions and a more sustainable future. The energy recovered from different sources in electric vehicles can be used in a variety of ways to improve vehicle overall efficiency and performance.

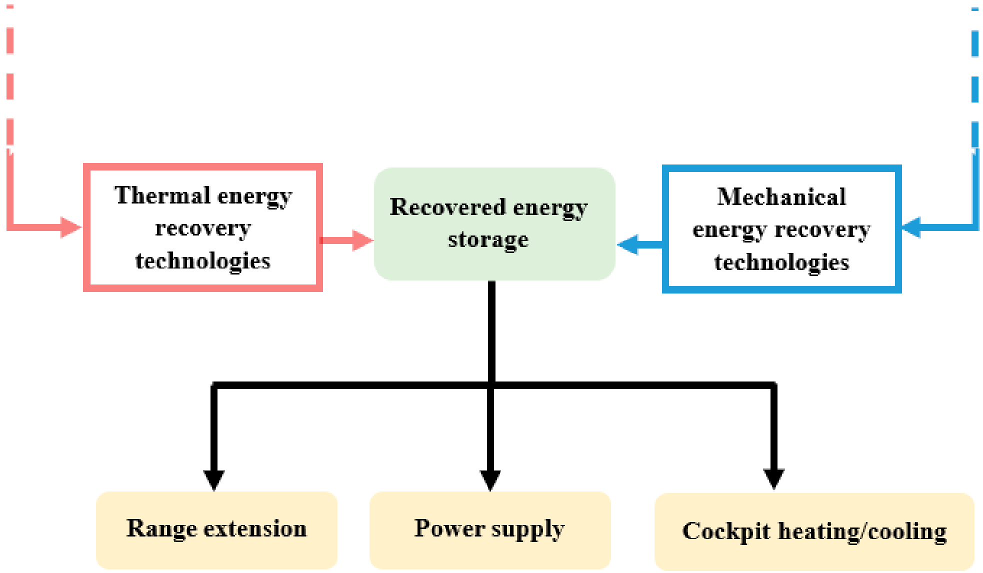

Figure 8. Use of recovered energy.

6.1. Range Extension

The process of increasing the distance that a vehicle can drive on a single charge or fueling is referred to as range extension. In the case of electric vehicles, this is accomplished by increasing battery capacity or lowering energy usage through various means, which can include optimized aerodynamics, lighter weight, and efficient powertrain components. Recovered energy can also help to extend range by enabling the vehicle to recapture energy that would otherwise be lost during braking or system operation. This energy can then be employed to recharge the battery and power the vehicle electrical systems. Efforts have been made in research to extend the range of electric vehicles using energy recovery techniques such as regenerative braking [14]. Despite their low fuel consumption and environmental effect, electric vehicles encounter range challenges due to battery energy density limitations [92]. Furthermore, the operation of air conditioning systems and certain battery characteristics can reduce the range of electric cars even further in extreme hot and cold climates [85,93].

6.2. Monitoring Sensors

Monitoring sensors are critical for measuring and tracking the quantity of energy recovered and reused in recovery systems. These sensors are used to measure a variety of parameters, including power output, temperature, speed, and other critical variables. Monitoring sensors guarantee that the energy recovery system operates efficiently and effectively. These sensors also cater for real-time system adjustments, guaranteeing maximum energy recovery and utilization. Monitoring sensors, which are often rated in watts or milliwatts, can be powered by energy harvesting systems, and most energy harvesting devices can provide the required energy. Displacement sensors, pressure sensors, distance sensors, weather sensors, omnidirectional sensors, and mobile sensors in intelligent transportation systems can enhance road safety and reduce the likelihood of accidents, saving lives and minimizing economic losses. These sensors are typically installed in vehicles and are powered by either battery or wired electricity [14,81–83].

6.3. Cockpit Heating/Cooling

Energy recovery can be used as an alternative energy source to heat and cool vehicle cockpits, lowering fuel usage and pollution. The range of electric cars can be extended by using recovered energy instead of conventional energy sources, and it can enhance both comfort and safety for passengers. Some research has also concentrated on utilizing residual heat from a heat pump to heat the passenger compartment, thus providing a convenient solution for both winter and summer temperature adjustments [14].

6.4. Power Supply for Low-Power Devices

Energy recovery can be used to power low-power devices such as sensors and instruments, which are frequently found in transportation systems. These devices have low energy requirements, typically measured in watts or milliwatts, which can be easily met by energy harvesting systems. The use of recovered energy as a power source reduces reliance on battery or wired power, resulting in better system efficiency and lower costs. The use of recovered energy improves transportation safety while also palliating environmental effects. The 12 V service battery in a car powers accessories such as the fan, radio, signals, and other devices. The recovery system can recharge this battery if required. Furthermore, using energy recovery systems as a power source for these low-power devices can reduce power consumption and costs while also simplifying power supply, because energy recovery systems can be installed close to the low-power devices.

7. Technical Challenges and Future Work

Energy recovery system implementation in transportation systems encounters a number of technical challenges that must be addressed in order to guarantee optimal performance and reliability. Optimizing energy harvesting methods, integrating energy harvesting systems into other vehicle components, and creating efficient energy storage systems are among these challenges. Furthermore, additional study and development is required to address problems such as energy efficiency, cost, and the durability of energy recovery systems in different environments. Addressing these issues and continuously improving energy recovery systems will be critical for the broad acceptance and success of these systems in the transportation industry.

In terms of comfort and limited room, the implementation of energy recovery systems in electric vehicles requires special consideration. The position of thermal energy recovery technologies must not interfere with the efficiency of the motor or battery and must not endanger passengers. The distribution of regenerative and mechanical braking forces must also be taken into account. To be readily replaced, the size of a regenerative shock absorber must be similar to that of a conventional shock absorber. Because of the installation of pipes and turbines, the position of recovery systems from aerodynamics must also be optimized.

Vehicle energy recovery systems must be optimized in order to balance regeneration efficiency and driving comfort. Most studies have concentrated solely on prototype performance, but real-world road evaluations are required to assess the actual performance of energy regeneration. A novel railway energy harvesting tie suggested in a paper [94] and aimed at improving rail safety and connectivity by bringing intelligence to the railway is one example of this. The system is intended for uses that require trackside power in remote areas and tunnels, where electrical power is required but difficult to supply for wayside safety devices, wireless communication systems, and health monitoring systems.

8. Conclusions

The implementation of energy recovery systems in transportation can potentially transform the way we travel. The potential benefits of these systems, including improved efficiency, cost-effectiveness, and sustainability, make them an important area of focus for the future of transportation. However, there are still several technical challenges that need to be addressed, such as optimizing energy harvesting techniques, integrating systems into other components of the vehicle, and developing efficient energy storage systems. Furthermore, more research and development is necessary to address concerns such as energy efficiency, cost, and durability in various environments. Despite these challenges, a widespread acceptation and improvement of energy recovery systems in transportation is crucial for a more sustainable and efficient future. This review highlights the potential of energy recovery for electric vehicles through various sources, including the battery, motor, brakes, ground–wheel interaction, aerodynamics, and shock absorbers. This recoverable energy can feature thermal and mechanical forms and be studied for different applications. It is crucial to continue researching and developing these systems to fully realize their potential for transportation. Overall, energy harvesting in electric cars offers improved range, efficiency, sustainability, cost savings, longer battery life, and flexibility in energy sources. All these assets render energy harvesting a highly valuable and advantageous practice for electric vehicle technology.

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