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Energy Recovery and Energy Harvesting in Electric and Fuel Cell Vehicles, a Review of Recent Advances

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ABSTRACT This review article examines the crucial role of energy harvesting and energy recovery in the design of battery electric vehicles (BEVs) and fuel cell hybrid electric vehicles (FCHEVs) as these vehicles have limited onboard power sources. Harvesting energy and recovering energy from onboard systems can significantly improve energy efficiency, increase range, and reduce fuel consumption. The latest advances in vehicular energy recovery and harvesting, including regenerative braking, regenerative suspension, solar and wind energy harvesting, and other recovery methods are studied and the impact of the energy storage system and powertrain architecture on energy harvesting is investigated. Regenerative brake control strategies and driver behaviour's effect on energy recovery are reviewed, and the potential of energy harvesting in electric vehicles is discussed, including experimental and low-power harvesting methods. The importance of using perception and navigation technologies in autonomous vehicles to enhance energy efficiency is highlighted. The article identifies critical research gaps, challenges, and future directions for research in this field. This review stands out from previous papers by covering overlooked subjects such as driver behaviour and deceleration planning in autonomous vehicles, low-power harvesting methods, and experimental techniques applicable to electric vehicles.

INDEX TERMS Autonomous vehicles, electric vehicles, energy harvesting, energy dissipation, fuel cell vehicle.

I. INTRODUCTION

For many years the energy market has been dominated by fossil fuels as the first choice for the transportation industry. However, the fossil fuel shortage and its price, alongside the environmental crisis, have shifted the focus of the automotive industry toward a new generation of vehicles [1]. The recent rise in the EV market in China is a good example of it (Fig. 1). This shift is happening in not only the automotive industry but also in the aerospace and marine industries. This change of trend is in favor of electrical vehicles (EVs). The term EV

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refers to vehicles that fully or partially use electric motors for traction. Surprisingly, the idea of employing electric motors to drive a car emerged many years ago. From 1897 to 1900, 28 percent of the total vehicles in the market were of an electric type and were preferred over internal combustion engine (ICE) ones [2]. However, the lower price of oil and the limited range of electric vehicles in that era turned the tide. The reappearance of electrified vehicles in the market was first in the form of hybrid electric vehicles (HEVs) in the 1990s. These vehicles benefit from electric and fossil power sources, for instance, the very successful Toyota Prius model [3]. HEVs combine the drive powers of an ICE and an electrical machine to achieve higher fuel efficiency than

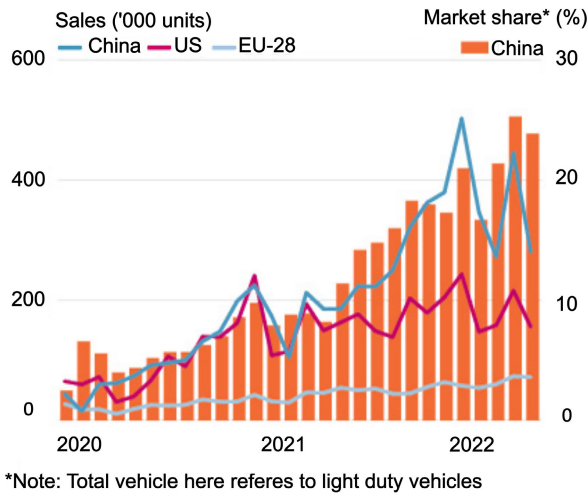


FIGURE 1. The rise in the EV market in China [6].

ICE-only vehicles [4]. There are two basic configurations for the HEV powertrain: Parallel and Series. In the series HEV topology, a generator, driven with ICE provides the electrical power alongside a power storage unit for an electric motor that drives the wheels. In parallel HEV, the power generated by an ICE and an electric motor is merged to drive wheels. In the combined configuration of the HEV powertrain called series-parallel (SP-HEV), the vehicle combines the advantages of both series and parallel configurations, but it has a more complex powertrain and power flow control [5].

In a different classification, HEVs can be classified into four types based on their degree of hybridization: mild HEV, medium HEV, full HEV, and plug-in hybrid electric vehicle (PHEV). Mild HEVs use electricity during stopping and braking events, allowing the ICE to turn off, but do not have a fully electric mode. Medium HEVs can run in fully electric mode for a limited time, in addition, the electric motor (EM) can operate in parallel with ICE. The main difference between a medium HEV and a full HEV is the battery size. Full HEVs have larger battery packs so they can run long distances. PHEV applies both ICE and an electrical powertrain like a normal HEV, but the electric drive acts as the main drive which means PHEVs tend to have batteries with more capacity compared to other HEVs. The difference between PHEV and full HEV is the capability of PHEVs to be connected to the power grid for charging [7].

An EV, that only relies on an electric drivetrain is called a full electric vehicle (FEV). Today battery electric vehicles (BEVs) that only rely on batteries to drive electric motors are very popular. An additional source of electricity can be obtained from a fuel cell which acts as an onboard unit for electricity generation. A fuel cell electric vehicle (FCEV) relies on hydrogen as a fuel with high specific energy to generate electricity and this gives it the advantage of nearly net zero emission [7]. Fuel cell (FC) technology includes different types and among them, proton exchange membrane

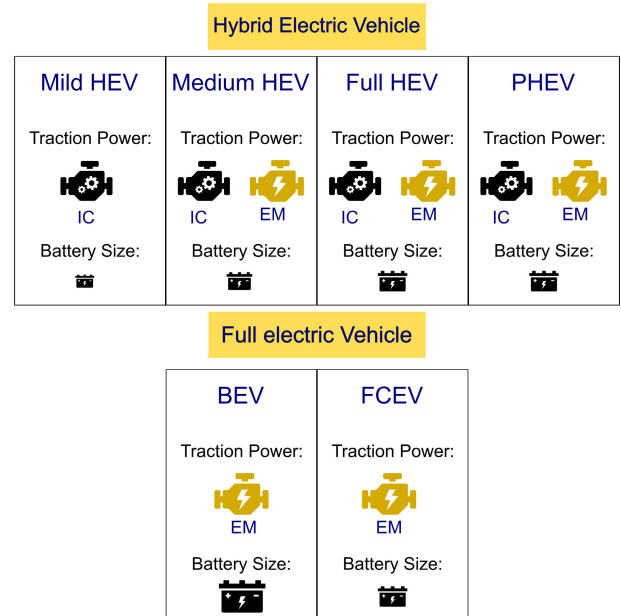


FIGURE 2. The classification based on dedicated traction.

fuel cell (PEMFC) is more promising in terms of applications related to the vehicle industry [8]. In general, a chemical reaction results in ionized hydrogen atoms with a positive electrical charge, and, by providing electrons with a negative charge a current will be produced through the circuit. The produced electricity is used to propel the vehicle or it is stored in an energy storage unit such as a battery or ultracapacitor or a combination of both [9]. It is possible to consider FC as the only source of energy, but it could be applied to only a limited sort of applications, because changing power demand causes problems, for instance, fuel cells should be sized for the maximum power demand [10]. Hybrid energy source facilitates high power demands and store regenerative braking energy, so FCEVs are also called Fuel Cell Hybrid Electric Vehicles (FCHEV) [11]. Table 1 compares different types of EVs. To keep the table as productive as possible some categories are not considered in the table and only widely accepted terminologies are mentioned. Fig.2 shows the classification based on dedicated traction.

Despite the promising prospect of using BEVs and FCEVs on a large scale, there are also other barriers ahead of their widespread application. Considering BEV, the charge station infrastructure is not well-developed yet. This includes a limited number of charge stations, especially in rural areas, and the electric network power shortage in peak hours. Moreover, the charging time of a typical electric car is still much longer than the refueling time of a conventional vehicle. Furthermore, as electric vehicles utilize numerous battery cells with a limited lifetime, the recycling of degraded batteries is an environmental concern. The available resource of Lithium is a controversial topic and while some researchers have indicated insufficient resources for BEV, others have found this claim questionable. Despite these opposing ideas,

TABLE 1. Characteristics of different EV types.

	Subgroups of EVs	Traction Element	Energy Source	Characteristics
Hybrid Electric Vehicle (HEV)	Parallel HEV	EM and ICE	Battery Ultracapacitor	<ul style="list-style-type: none"> • Complex space packaging due to the need to couple EM and ICE • Smaller energy loss than series HEV • Relatively cheap drive train
	Series HEV	EM and ICE	Battery Ultracapacitor	<ul style="list-style-type: none"> • Some complex mechanical parts are replaced since the wheels are driven by an EM • Smaller and more efficient ICE that acts as a generator • Conversion of energy from electrical to mechanical reduces the overall system effectiveness
	PHEV	EM and ICE	Battery (large) Ultracapacitor	<ul style="list-style-type: none"> • The longer range on the battery than other HEV • The cost of battery replacement is high
	SP-HEV	EM and ICE	Battery Ultracapacitor	<ul style="list-style-type: none"> • Very complex power train • Optimized function
Full Electric Vehicle (FEV)	BEV	EM	Battery Ultracapacitor	<ul style="list-style-type: none"> • No need for fossil fuel • High cost • Charging time is considerably long
	FCEV	EM	Fuel Cell Battery Ultracapacitor	<ul style="list-style-type: none"> • No need for fossil fuel • High cost of fuel cell • Availability of fueling stations • Better energy management and fuel consumption

approximately 74 percent of known lithium resources are located in South America and the market is very vulnerable to geopolitical risks [12]. Finally, the limited range is one of the most critical obstacles for BEVs.

FCEVs have some advantages over BEVs, for instance, it only takes 3-5 minutes to refuel a FCEV which is significantly quicker than BEVs and satisfies customer needs for normal applications [13]. Nevertheless, there are even more challenges compared to the BEVs. Fuel cell low durability is a major consideration since current commercial FCEVs offer a fuel cell life span that is considerably lower than other competing technologies. The high cost of fuel cells and hydrogen is another barrier to the widespread use of these vehicles. The majority of hydrogen production relies on the hydrocarbon reforming process [14]. So, in terms of cost-per-kW, it is more expensive than the direct use of fossil fuel and without a renewable source, it is not clean energy. In addition, hydrogen refueling infrastructure and storage systems are the bottlenecks for its fast development [15]. Lastly, the slow dynamics of the fuel cell limit the characterization of the system.

To tackle these problems a wide variety of solutions are investigated in the scientific community. One solution would be a photo-voltaic hybrid electric vehicle (PVHEV) that uses solar energy to charge batteries. However, PVHEVs are still in the developing phase [4] and are inefficient in areas with low sunlight. Investigating new battery chemistry to maximize energy density has been an attractive field for many studies [16], [17], [18], [19], [20], [21]. In addition, research regarding optimizing the fuel cell stack is an answer to overcome fuel cell-related shortcomings [22], [23], [24], [25]. Besides, the optimization of energy management contributes

to facilitating the implementation of BEVs and FCEVs [26], [27] [28]. Recovering the dissipated energy in vehicles is an efficient approach to decreasing energy consumption in BEVs and FCEVs.

To have a better understanding of energy harvesting advantages, it is necessary to break down the energy usage in an EV. To measure energy loss and use in an EV, it is important to consider the vehicle type, because these factors may vary from one vehicle to another. Furthermore, different driving patterns can affect energy requirements in an FEV. Despite these varying numbers, a general idea about energy flow can be illustrated. When a vehicle moves due to friction and air drag, it dissipates energy. Also, when a vehicle is turned on there is a minor power use for applications like controls, dash lights, etc. For an EV driving on a highway energy loss in an electric drive system is 15 percent, 5 percent less than an EV in stop-and-go drive cycles. Energy loss in accessories on the highway is 2 percent compared to 4 percent in the city. Auxiliary electrical devices are responsible for 0 percent to 2 percent of energy loss on the highway and 0 percent to 6 percent in the city. Finally, 71 to 73 percent of the energy is delivered to wheels on the road. This number is approximately 60 to 66 percent for an EV in stop-and-go scenarios [29], [30], [31], [32], [33]. Fig.3 illustrates the average dissipated and used energy in an EV based on the drive cycle.

Harvesting and recovering energy can be implemented in various types of transportation, including marine vessels, UAVs, trains, and vehicular applications. However, the challenges and opportunities to harvest and recover energy in each type of transportation vary. In the automotive context, energy can be obtained through different methods such as

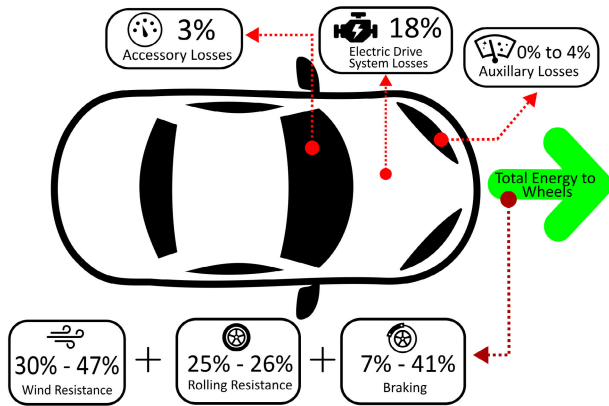


FIGURE 3. Energy loss in the electric vehicle based on city and highway driving cycles based on the data provided in [29], [30], [31], [32], and [33].

regenerative braking, regenerative suspension, solar harvesting, RF energy harvesting, and more. One crucial aspect of energy harvesting and recovery systems is their compatibility with established protocols and industry guidelines. These guidelines comprise safety standards, durability, reliability, and ride comfort. In this paper, the possibility and the amount of available energy to harvest energy marks regenerative braking as the most promising source, and a comprehensive review of strategies and challenges regarding regenerative braking will be presented. Moreover, a short review of other harvesting potentials will be carried out. In the majority of published review papers, the differences between FCEV and BEV are not taken into account as they apply different energy management strategies. In addition, the battery size in FCEV and BEV are not the same and this makes a huge difference in the ways they use the harvested energy which will be explained in the next sections.

A. SEARCH STRATEGY AND ARTICLE SELECTION

To conduct a comprehensive review of energy harvesting and energy recovery in BEVs and FCEVs, electronic databases were searched using specific keywords. Articles older than 2010 were excluded (note that some references older than this date have been used in this article for general explanations). The selected studies focused on EVs and FCEVs, or their findings were applicable to these vehicle types. The process and criteria for selecting references are illustrated in Fig. 4. Although topics such as heat energy recovery or aerodynamic design of vehicles were related to the scope of this review paper, they have been excluded due to extensive previous studies and their similarity to both conventional and alternative fuel vehicles.

B. CONTRIBUTIONS

Several works have been done on energy harvesting in vehicles. However, to the best of the authors’ knowledge, no comprehensive study has been carried out in this regard which mainly focuses on BEVs and FCEVs. Hybrid vehicles

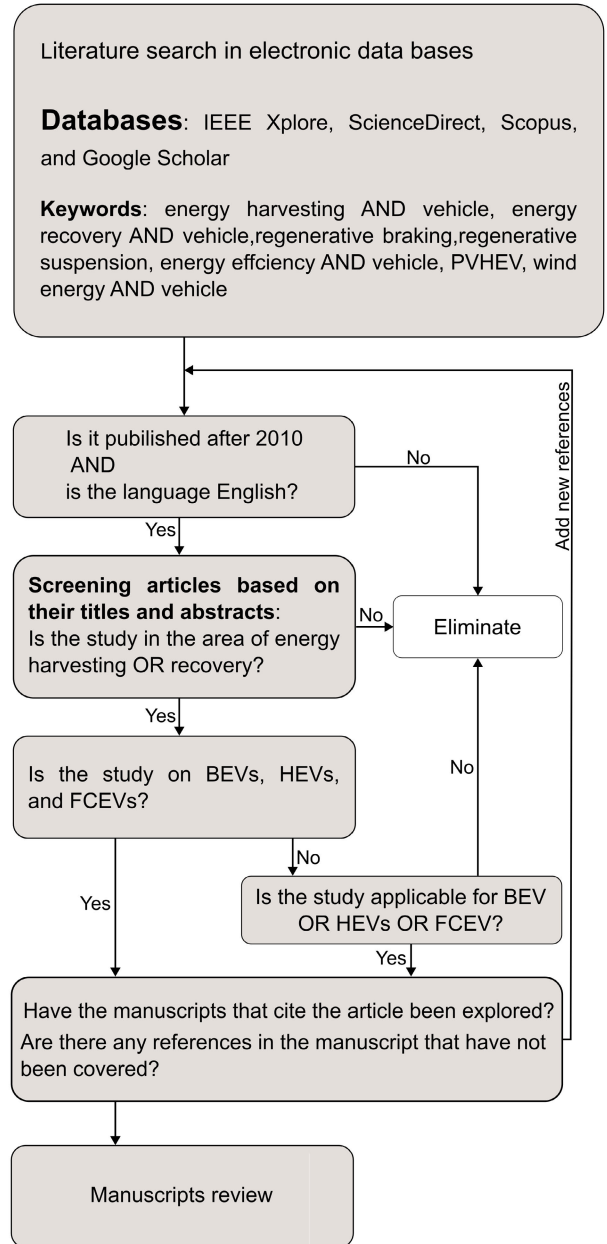


FIGURE 4. The process of selecting references.

include an IC which converts only the friction of fuel energy to useful work and the rest is lost as heat. There are various approaches for recovering heat from IC and it has been already studied in numerous works. In this paper, we are not covering IC heat recovery, and readers are referred to existing research. Excluding ICE and thermal energy recovery (TER) helps this review in two steps. First, it allows us to look deeper at the relationship between EVs architecture and energy harvesting. And second, we can focus on more recent energy recovery methods. For instance, in recent years there is an increasing trend toward energy harvesting in autonomous EVs. Covering energy harvesting in autonomous BEVs and FCHEVs is another difference between the proposed study

and similar works. In addition, the impact of human drivers' behaviour and autonomous navigation on energy harvesting is presented. Moreover, the methods of low-power energy harvesting such as radio frequency energy harvesting or rim-mounted devices are presented. Table 2 compares recent related review papers with this review.

C. THE STRUCTURE OF THE REVIEW

Before investigating the potential sources for energy harvesting, there will be a review of the energy storage systems in EVs and the related architectures in BEVs and FCEVs. Covering energy harvesting methods begins with regenerative braking considering different influential factors such as control strategy and inputs, driver behaviour, and autonomous driving. It follows with a review of energy harvesting in the suspension system and specific applications in EVs. In the next section solar, wind, and other harvesting methods are analyzed. Finally, current challenges and gaps are mentioned.

II. FEV ARCHITECTURE

The powertrain architecture of FEV may include batteries, ultracapacitors, fuel cell stacks, converters, and inverters. The combination of these parts results in different architectures and developing a deeper understanding of them helps to realize energy loss in FEV.

A. BEV ENERGY STORAGE SYSTEM (ESS)

The ESS of a BEV may include a battery, UC, or both and it may contain different types and numbers of DC converters.

1) BATTERY

There are various types of batteries available and widely accepted in the market: Lead-acid batteries, Nickel-Cadmium (NiCd), Nickel-Metal-Hydride (NiMH), Lithium-ion (Li-ion), Lithium-ion Polymer, and Sodium Nickel Chloride (NaNiCl) [40].

a: LEAD-ACID

Lead-acid batteries are the earliest form of battery technology and are still widely used today due to their low cost of production and impressive power-to-weight ratio. However, when it comes to batteries for use in fully electric vehicles (FEVs), lead-acid batteries may not be the best choice. This is because FEV batteries need to be able to operate at a partial-state-of-charge (PSOC) in order to efficiently accept rapid charging, something that traditional lead-acid batteries are not designed to do [41]. As a result, the energy harvesting capacity of these batteries can be reduced, making them less than ideal for use in FEVs.

b: NiCd

This technology has also been around for more than a century. Its long-life cycle sounds promising in terms of use in the FEV industry, but it has low energy density. More importantly, it contains a highly toxic element of cadmium [42]. It can cause environmental problems and

threats to all living organisms, even in very low amounts. These issues indicate that its usage will be limited in many applications including FEVs [43].

c: NiMH

NiMH battery is capable of rapid charge which is an interesting feature for EVs. Being maintenance-free and having long life makes it a typical choice for HEVs including PHEVs [44]. However, their storage capacity is lower than Li-ion batteries and they are more expensive compared to lead acid batteries.

d: LI-IO

Li-ion batteries first appeared in 1985 and six years later they were commercially available. These batteries have a high energy storage capacity and considerable energy density, also Like NiMH, they are capable of rapid charging. Currently, the ESS market for FEVs is dominated by li-ion technology [45]. The other important characterization regarding Li-ion batteries is the low self-discharge rate and a wide range of operating temperatures.

e: LITHIUM-ION POLYMER

With its higher energy density, this battery technology has quickly gained popularity in the portable electronic device market and has even surpassed other types of batteries in terms of usage. However, despite these benefits, certain factors have prevented its widespread application in larger-scale implementations, such as in fully electric vehicles (FEVs). Safety issues, as well as concerns surrounding the overall cell life and performance of these batteries, have hindered their adoption in this context [46]. Nevertheless, efforts are underway to address these issues and explore the potential of this technology for broader applications.

f: NaNiCl

These batteries also referred to as Zebra battery has been reported as the best choice regarding energy consumption since they have a high energy density [47] but the current problem in terms of operational safety is stopping them from being widely used.

2) ULTRACAPACITOR

Ultracapacitors (UC) are energy storage units that store energy without any chemical reactions. Therefore, they have a long-life cycle and higher power density compared to batteries. This makes UC a good candidate for capturing regeneration braking energy in EVs as they are capable of quickly capturing and delivering electric energy peaks. However, they suffer from a high discharging rate and low energy density. These characteristics affect their effectiveness choice as the sole component in an ESS. On the other hand, batteries have a high energy density and a hybrid energy storage system (ESS) including the combination of

TABLE 2. Comparison between the presented review and recent related reviews.

Review papers	Year	Cover regenerative braking	Cover regenerative suspension	Focus on BEVs	Focus on FCEVs	Considering autonomous vehicles	Driver impact on energy recovery	Solar and harvesting	Wind and harvesting	Experimental low-power harvesting	Considering energy storage system
[34]	2021	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗
[35]	2021	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
[36]	2018	✓	✗	✗	✗	✓	✓	✗	✗	✗	✗
[37]	2018	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
[38]	2022	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓
[39]	2021	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓
The presented review paper	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

batteries and UCs is very promising in terms of designing a well-rounded ESS for EVs with greater efficiency [4], [48].

3) BEV ARCHITECTURES

An ESS only consisting of a battery results in two architectures: the battery is directly connected to the AC inverter, or it is connected to the DC converter, and the converter is linked to the inverter. In the former architecture, the DC-link voltage varies greatly but in the latter one, the bidirectional DC/DC converter controls the power flow [49]. The combination of the battery and UC results in different configurations which are: Passive parallel, fully active, and semi-active. The semi-active configurations are UC/battery and battery/UC, and the fully active configurations are cascade (series), parallel, and multiple input converter configurations. Fig.5 shows different hybrid ESS configurations. The passive parallel configuration is very simple and since there is no control between two units the utilization of UC is not completely effective [50].

Regarding the semi-active configurations, in UC/battery configuration the DC/DC converter is interfaced with UC, and the battery is connected directly to the DC link. In this setup, the battery is protected yet, but the UC operates inefficiently. In battery/UC configuration the direct connection of UC to the DC link results in the working of UC as a low pass filter and the DC link voltage is allowed to vary [51].

In fully active configurations decoupling UC and battery leads to more accurate control. In the cascade or series topology stabilizing the terminal voltage of the battery pack is simpler. In parallel fully active topology, the battery and UC are connected to the DC bus with separate bidirectional DC/DC converters that grant considerable flexibility. The multiple-input converter configuration decreased the cost of parallel while maintaining the separate control of the battery and UC [52].

As it was mentioned the control advantage of applying a converter comes with the cost of energy loss, which can happen during spending or harvesting the energy. Considering the energy architecture of the EV or FCEV we

can employ strategies that minimize energy loss. For instance, for vehicles with hybrid energy sources, it is beneficial to limit the number of occasions on which the IC or FC charges the ESS and should rely on energy harvesting to do so.

B. FC AND ENERGY STORAGE SYSTEM ARCHITECTURE

To highlight the different approaches regarding BEV and FCEV, it needs to have a deeper look at FCEV and the different architectures studied in the literature as they are in the early phase of development [53].

1) FUEL CELL

The characteristic of FC is ideal for providing constant power in applications like forklifts, submarines, and buses which are considered slow-speed vehicles [54]. FC has slow dynamics, and it is also affected by other factors like temperature and fuel delivery system performance. Therefore, it cannot satisfy rapid load demands without voltage drop known as the fuel starvation phenomenon. Consequently, it is necessary to have an auxiliary power source to help with peak power and store harvested energy [55]. Based on that, FC acts as the main source of energy for the vehicle, and another auxiliary source, that is capable of delivering and storing extra power is also used. Batteries and ultracapacitors are the most common ones in FCEV and different configurations of these sources have been studied in the literature.

The combination of FC, battery, UC, and DC/DC converter results in six topologies that have been studied in the literature [28], [54] [56]. Fig.6 depicts these topologies. Direct use of both FC and ESS without a DC/DC converter (T2) is not common in vehicles because ESS and FC must operate at the same voltage, this setup is used in aircraft applications [57]. Other topologies are suitable for vehicular applications but the mainstream design for most FCEVs is the combination of fuel cell and battery (T2 and T4 in Fig.6) [58]. Topologies including both battery and UC suffer from losses of power flow and as a result, they are complex in terms of control, but it has been reported that they have the highest energy conversion efficiency among others [59].

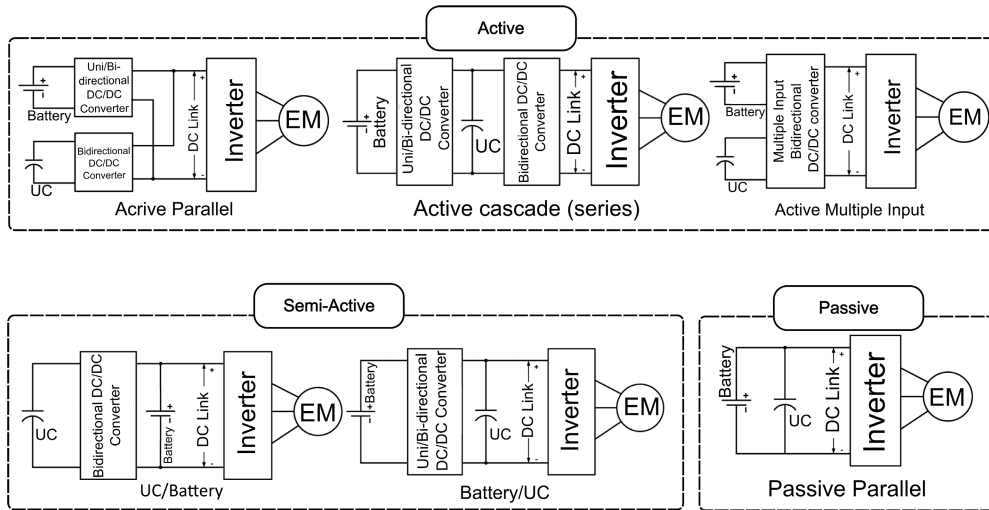


FIGURE 5. Hybrid ESS configurations in EVs [51].

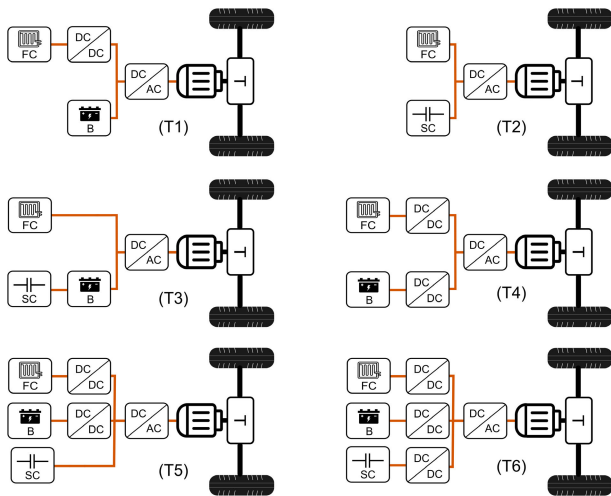


FIGURE 6. Different architectures of FCEVs [56].

2) DIRECT AND INDIRECT

Although the mentioned topologies cover all configurations, many studies have preferred to categorize the hybridization of FCEVs into direct (passive) and indirect (active) classifications [60]. The key difference between these two classifications is the use of DC/DC converters for the FC system. In the direct configuration, FC is connected to the DC bus or battery with a direct link while in the indirect type, FC (or ESS) firstly is connected to the unidirectional DC/DC converter, and then it connects to the DC bus alongside the ESS [27].

DC/DC converters shift the level of voltage in addition to stabilizing their output with unstable input. In the FC, it increases the voltage level from the fuel stack output to the voltage available at the DC bus. Based on the high voltage and low voltage demand, different DC/DC converters are used

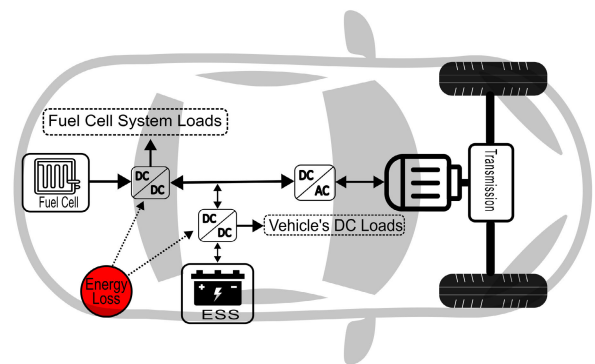


FIGURE 7. The most common architecture of FCEV and energy loss in converters.

in an EV or FCEV and a DC/AC inverter converts the DC input into three phases of voltage suitable for the EM [61]. The direct type offers low power loss and lower cost due to removing a DC/DC converter but as it was mentioned the operation procedure is very limited as discrepancies in the voltage-current behaviour of FC and ESS may occur [62]. Implementing a high gain converter in the indirect type gives control and is the best solution to the problem of low voltage and high current of FCs but the trade-off is energy loss at voltage converters [60]. Fig.7 shows the structure of indirect hybridization indicating the energy loss in the most common configuration in FCEVs. The DC/DC converter connected to the ESS is bidirectional, so in the occasion of capturing the braking energy, it can be used to charge the battery during cold start or high-power demand it supplies the system.

It is noteworthy to mention plug-in fuel cell electric vehicles (PHFCEV or PFCEV) that apply FC and battery hybridization. PFCEVs have a battery with a higher capacity to run on pure battery mode for a longer time and they can

be charged from the electric grid similar to conventional PHEVs mentioned before [63]. The combination of hydrogen fuel cells and BEVs offers many benefits as it facilitates the refueling process but a more complex design is required [64].

III. REGENERATIVE BRAKING

Based on the information provided in Fig.3, the major part of the energy is directed to the wheels to accelerate the vehicle and drive at a desirable speed. A moving vehicle's energy is lost by a considerable amount during the process of braking. The kinetic energy is converted to heat between the brake pads and the wheel. In cities with heavy traffic, more than half of the energy is dissipated in stop-and-move patterns [65]. Recapturing this wasted kinetic energy is the main idea of regenerative braking. During the regenerative braking process, the EM acts as a generator and produces a negative torque on the wheels. In this way, part of the kinetic energy is converted to electrical energy stored in the ESS [66]. Fig. 8 depicts the process of regenerative braking. The EM is not the only means to conserve energy and a hydraulic pump motor can also be used to store energy in a high-pressure accumulator. The flow between a low-pressure accumulator and a high-pressure accumulator can apply the stored energy for driving the vehicle in time of demand [67].

The longitudinal vehicle dynamic can be used to present the amount of regenerative brake power. According to Newton's second law of motion:

$$m \frac{dv}{dt} = F_T(t) - F_{res}(t) - F_b(t) \quad (1)$$

In this equation, $m = m_0 + m_r$, is the total effective mass, including the total sum of the vehicle's mass, m_0 , and m_r which shows the inertia of all rotating parts. F_T is the traction force, and F_b is the applied braking force. F_{res} represents the road loads and it can be shown as [68]:

$$F_{res} = mg(\sin\theta(s(t)) + C_{rr}\cos\theta(s)) - \frac{\rho_a A C_D v(t)^2}{2} \quad (2)$$

In the given equations, various factors contribute to the overall resistance experienced by the vehicle. These include the coefficient of rolling resistance, C_{rr} , the road slope represented as a function of position s , denoted by θ , the vehicle's front area, represented by A , the drag coefficient, denoted as C_D , the air density, denoted as ρ_a , and the vehicle speed, represented as $v(t)$. Additionally, the cornering resistance can be expressed as $C_r \frac{m^2 v(t)^4}{R(s(t))}$, where $R(s(t))$ represents the radius of curvature out of the plane of the image, and C_r represents the cornering coefficient. However, the cornering resistance is usually considered negligible due to the relatively small magnitude of C_r , which is typically on the order of 10^{-5} [68].

The total braking force (F_b) is comprised of friction braking force and regenerative braking force as shown in equation 3 [69]:

$$F_b = F_{Frc} + F_{Rgn} \quad (3)$$

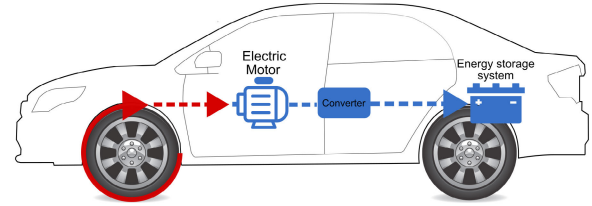


FIGURE 8. Regenerative braking in an EV.

Several factors affect regenerative braking, including the vehicle's mass, speed, road slope, air resistance, rolling resistance, and the allocation of friction brakes. The electric power delivered to the EM or generated during regenerative braking, P_m , is a function of motor torque ($T_m(t)$) and rotational speed ($\omega_m(t)$) as it is shown in equation 4. It is generally tabulated as the EM efficiency map or "motor map" [68]:

$$P_m = f(T_m(t), \omega_m(t)) \quad (4)$$

There are a variety of configurations for the drivetrain of EVs. In a simplified model we can assume that the EM and wheels are connected through a transmission with a fixed ratio g_0 . The rotational speed and torque of the wheels can be calculated as:

$$T_w = g_0 T_m \quad (5)$$

$$\omega_w = \frac{1}{g_0} \omega_m \quad (6)$$

The motor map depends on the type of machine. Fig.8 depicts an example of a motor efficiency map. based on the reversible application of EM, it can operate as a motor ($T_m > 0$) or as a generator ($T_m < 0$). The battery power, P_b , can be shown as $P_b = V_c I_c$, where v_c and I_c are the charging voltage and charging current of the battery respectively. In the regenerative mode, the relation between the charging power of the battery and the motor power can be described as motor-to-battery regenerative efficiency η , which is shown in equation 7 [70].

$$\eta = \frac{V_c I_c}{T_m \omega_m} \quad (7)$$

A. ENERGY STORAGE SYSTEM FOR REGENERATIVE BRAKING

ESS plays a principal role in regenerative braking. The possibility of using the recaptured energy depends on ESS and it is important to consider its limits to maximize the harvested energy. Storing the braking energy in a high-pressure accumulator in refuse collection vehicles and buses has been investigated [72], [73]. A combination of a hydraulic drive system and a braking strategy is reported to be effective regarding energy regeneration [74]. In other types of energy storage systems, like the spring energy storage system, the kinetic energy during the braking process is stored in

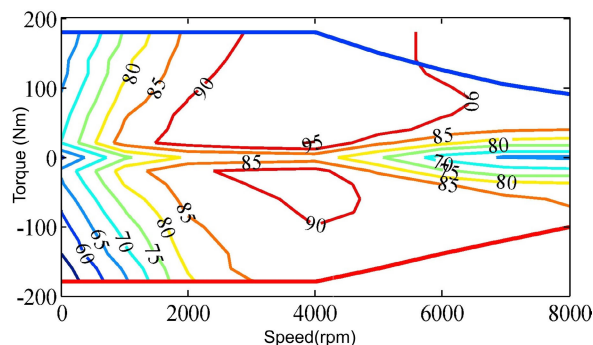


FIGURE 9. Example of EM efficiency map [71].

a compressed spring and the potential energy of the spring converts back into kinetic energy when required. Hydraulic energy storage systems, spring energy storage systems, and flywheel energy storage systems that store the kinetic energy of a rotating flywheel have been discussed comprehensively in the literature [38]. Since this paper's focus is on FEVs, the focus is on batteries and ultracapacitors which have shown high efficiency in this type of vehicle [75]. Table 3 presents a comparison of various ESS utilized for capturing regenerative brake energy. The table provides examples of references that have applied these ESS.

As it was mentioned before, batteries are the most common form of ESS in FEVs and play a significant role as the regenerative braking generates a high power as it is active. Battery capacity which is shown and measured in ampere-hours (Ah), voltage level, and battery power vary based on the different types of battery. The other important factor in batteries is the state of charge (SOC) which is very important in the process of regenerative braking. For all types of batteries and in particular lead-acid batteries, SOC strongly affects charge acceptance which is a significant factor during regenerative braking [87]. Besides the SOC, the other challenge for regenerative braking regarding batteries is temperature. These two factors strongly impact the FEV's ability to harvest braking energy.

Li-ion batteries have a wide range of operational temperatures but in fact, considering charging operations, there is a major obstacle that deeply affects battery function and hence energy harvesting. Low temperature causes several issues for Li-ion batteries and regarding energy harvesting capability; reduction in the available energy of the battery is the main problem [88]. This issue limits the energy harvesting potential in countries with many sub-zero temperature days, for example, Canada, Norway, and Russia. The application of lithium-ion batteries in cold weather has been reviewed in the literature comprehensively [89]. Battery preheating strategies, as a solution for FEVs in cold temperatures, have been reviewed in the literature [90]. In [91], a novel approach has been suggested to harvest braking energy not only to charge the battery but also to heat the battery. A control strategy was applied to activate the self-heating of Li-ion batteries during braking and rest intervals in driving.

For the batteries with smaller capacity, the ability to recapture the energy is limited and this is the case in the FCEVs as the charging current is also limited. Toyota Mirai and Hyundai Nexo are two commercially available FCEVs in the market, Mirai has a battery capacity of 1.2 kWh and Nexo has a 1.6 kWh battery. These numbers are considerably lower than the battery capacity of BEVs, for example, the Tesla Model 3 has a 60 kWh battery pack. Many researchers have assumed batteries with large capacity in their research, close to BEV's capacity. In [92], 25 kW was considered to design a fuzzy logic power management strategy for an FCEV. In [93], an energy management system (EMS) has been proposed to improve fuel economy in an FCEV having a battery with a capacity of 38 kWh, furthermore, a 13 kWh battery was part of the model specification in [94] where a sub-optimal EMS was studied on FCEV.

It is worth mentioning that the effect of energy harvesting in the brake system in Li-ion batteries has been investigated and no detrimental effect on battery life has been reported [95]. In fact, as limiting the depth of discharge extends the battery life [96], regenerative braking supports longer battery life. In section II, the benefits of hybrid ESS were covered. In [97], a hybrid energy storage system (HESS) of battery and ultracapacitor with a switching algorithm is used to provide a simple and highly efficient method for energy regeneration of brakes. The method is reported to improve efficiency by about 20 percent. Also, a HESS has been tested alongside a multi-object optimization problem to extend the battery life [98]. In [99], the effect of using UC in HESS in FCEVs has been explored and it was found that the use of UC increases the performance to recapture more kinetic energy of FCEV during a braking event. In the mentioned research, the application of batteries with low capacity in a commercial FCEV was considered.

From a safety standpoint, proper maintenance and regulation of ESS (Energy Storage Systems) is crucial. It involves managing charging capacity, temperature, SOC (State of Charge), and state of health. Poor control of these parameters can hinder RBS (Regenerative Braking Systems), harm the ESS, and vehicle and passenger safety. Fire accidents in the formula one vehicle with regenerative braking and electric ESS is an example of it [38].

B. REGENERATIVE BRAKING CONTROL STRATEGY

Electric vehicles with regenerative braking systems are also equipped with conventional friction brakes and based on this configuration there are three states during the braking process:

1) FIRST

EV may only depend on regenerative braking to stop, and all the braking energy is recaptured. In this case, the friction brake is not used. when the demand for deceleration is not high and immediate, vehicles could operate in this state.

TABLE 3. Various ESS for regenerative braking system.

Type of ESS	References	Advantage	Disadvantage
Battery	[76], [70], [77]	<ul style="list-style-type: none"> • High energy density • Already available for BEVs and FCHEVs • Mature technology 	<ul style="list-style-type: none"> • Limited charging current • Pollution from battery
UC	[78], [79], [80]	<ul style="list-style-type: none"> • Fast response and charging • High power density 	<ul style="list-style-type: none"> • Some complex mechanical parts are replaced since the wheels are driven by an EM • Smaller and more efficient ICE that acts as a generator • Conversion of energy from electrical to mechanical reduces the overall system effectiveness
Flywheel	[81], [82], [83]	<ul style="list-style-type: none"> • High energy density • Eco-friendly 	<ul style="list-style-type: none"> • Heavy weight and needs extra space • Not possible to save energy for long periods
High-pressure accumulator	[72], [73], [74]	<ul style="list-style-type: none"> • High power density • High charging and discharging rate 	<ul style="list-style-type: none"> • Need space, not suitable for passenger vehicles • Heavy weight
Spring	[84], [85], [86]	<ul style="list-style-type: none"> • No energy loss in conversion 	<ul style="list-style-type: none"> • Complex mechanism • Heavy weight • Limited energy recovery

2) SECOND

EV uses both friction and regenerative braking simultaneously and each brake has a different share of total braking force which is called blending. Regarding blending, there are two classifications, serial, and parallel [100]. In parallel regenerative braking, both brakes are applied simultaneously. In serial regenerative braking, brake force is generated by regenerative braking unless the needed brake force exceeds a particular point [101]. Fig. 10 shows different classifications of braking and their effect on energy harvesting in a vehicle with only friction brakes on the rear wheel and both friction and regenerative brakes on the front wheel. In the serial, friction brakes on the rear and front wheels are applied when the required braking force exceeds a specified force.

3) THIRD

EV only applies friction brake to stop the car. The emergency stop is one reason for this braking scenario because of insufficient resistance torque produced by EM. With fully charged batteries also there is no need for harvesting braking energy. In addition, at low speeds, it is a challenging task for EM to act as a generator, therefore a low-speed threshold is considered, and at speeds below that, regenerative braking is inefficient and also harms the total performance of an EV [103]. The low speed in literature is considered 10 km/h and should be considered as a barrier to energy harvesting [104], [105].

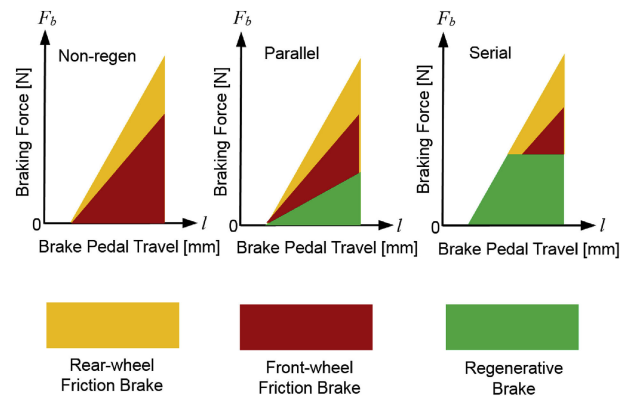


FIGURE 10. Serial and parallel regenerative braking [102].

From this perspective, energy harvesting efficiency is influenced by the control strategy employed to decide the allocation of regenerative and friction braking. A reliable control strategy is needed to guarantee the safety and stability of the vehicle in braking events and maximize regenerative braking. In addition, driving comfort is another important factor that should be considered alongside braking performance and energy recovery rate [106]. Stability, safety, and energy recovery can be considered the main goals of a regenerative braking system (Fig.11).

Different control strategies and controllers have been investigated in the literature [7], [38], [107], [108], [109].

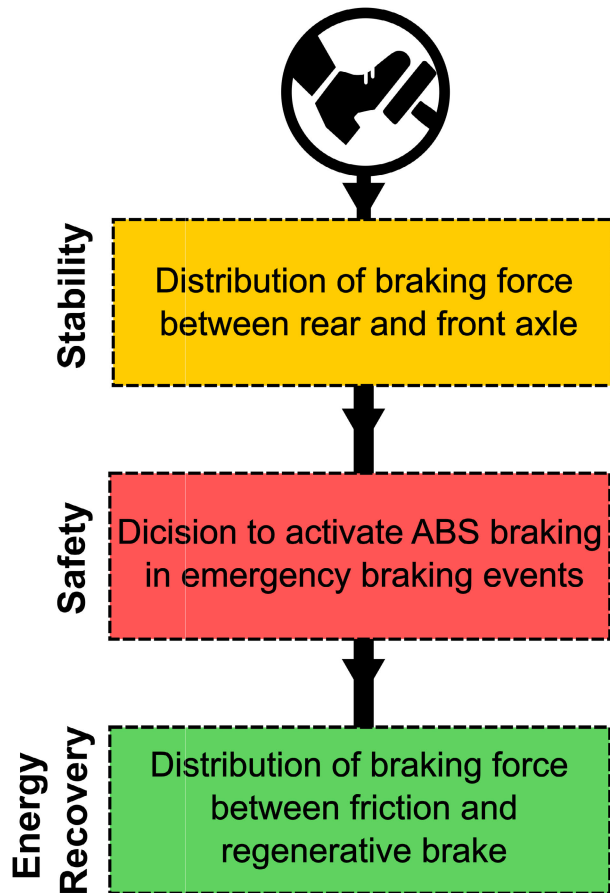


FIGURE 11. Main goals in the regenerative braking system.

The most common classification is by considering employed controllers and thereby fuzzy logic controllers, sliding mode controllers, PID controllers, neural network controllers, model predictive controllers, supervisory rule-based control, multi-layer controllers, and other methods are discussed.

4) REGENERATIVE BRAKING IN A CONVENTIONAL HEV AND BEV

Based on The National Highway Traffic Safety Administration (NHTSA), autonomous vehicles are defined in levels from 0 to 5. In level 0 the human driver has full control of the vehicle and in level 5 the vehicle is completely independent for driving which is called full automation. In level 1, acceleration, braking, and steering are assisted by the system driver is fully in control of the vehicle. Additional features like highway pilot are the difference between level 1 and level 2. In level three, the vehicle can perform a driving task, but the driver should be ready to get engaged. Level 4 is similar to level 5 but the service area in level 4 is limited [110]. Today conventional EVs belong to levels 1 and 2. Level 3 vehicles are emerging and research on upper levels is an interesting and popular topic for researchers. In this paper, conventional electric vehicles refer to levels 1 and 2.

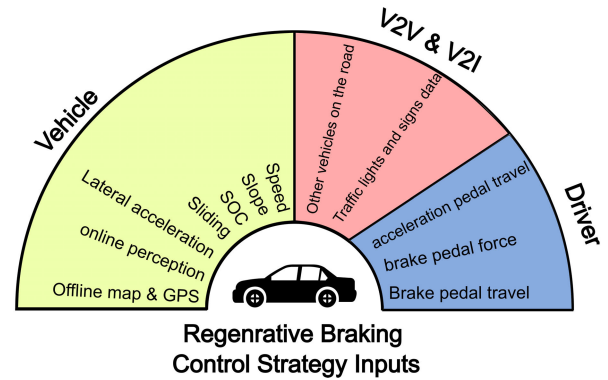


FIGURE 12. Different inputs of a regenerative braking control strategy.

The basic input for the control strategy of regenerative braking is signals from the brake pedal. A human driver creates this signal by the pedal travel and the force he applies to the pedal which results in the calculation of the requested brake force and the activating anti-lock system, if applicable. As it was mentioned before, the SOC of the battery is an important characteristic during regenerative braking. In addition, there are many other inputs from different sensors that have been applied, for instance, speed, the slope of the road in real-time, feedback from hydraulic brakes, etc [108]. The three most frequent factors for the control strategy are brake pedal force, speed, and SOC [111]. Fig. 12 shows different inputs that can be considered to design a regenerative braking control strategy.

In [112], a regenerative braking control strategy based on fuzzy logic control was proposed, considering inputs such as required braking force, vehicle speed, and SOC. The output was regenerative braking allocation in total braking force, leading to increased vehicle system efficiency. Lv et al. [113] studied a similar control strategy for an HEV with the EM on the rear axle, where the fuzzy controller determined the share of regenerative brake force in the total braking force. Xu et al. [114], [115] applied the same approach to a four-wheel motors EV, considering SOC, brake force, and vehicle speed as inputs. Saradalekshmi and Binoj Kumar [116] utilized SOC, brake force, and vehicle speed as inputs for their fuzzy controller in a BEV, with the output serving as the input for a PI controller. Ko et al. [117] introduced cooperative control of regenerative and friction braking force allocation by considering pedal stroke, gear step, and vehicle step. Xiao et al. [118] integrated brake strength, SOC, and motor speed into their fuzzy logic controller, considering emergency situations with mechanical braking and EBD in a BEV. Ji et al. [119] developed a regenerative braking strategy considering accelerator and brake pedal inputs, SOC, and vehicle speed, demonstrating an increase in energy recovery. Wen et al. [120] used an adaptive fuzzy controller for single-pedal regenerative braking, considering stroke change and gradient as inputs. These studies highlight the utilization of fuzzy logic control in early regenerative braking strategies, incorporating multiple inputs to improve energy recapture in electric vehicles.

In their work, Ruan et al. [106] proposed a cooperative algorithm that integrated regenerative braking with driving assistance features like ABS and EBD. The algorithm considered brake signals, regenerative braking limitations, motor torque, gear ratio, and battery charge. It included three blending strategy modes prioritizing energy saving, anti-lock capability, and safety.

A regenerative braking control strategy was proposed by [121] based on nonlinear model predictive control (NMPC) to ensure stability and maximum braking energy recovery. The stability was ensured by distributing braking force on the front wheels with pneumatic brakes and rear wheels with pneumatic and regenerative brakes. The distribution of brake force between pneumatic and regenerative was also optimized to maximize the recovered energy. A longitudinal model with seven degrees of freedom was developed and input variables for NMPC were vehicle speed, front wheel rotation speed, rear wheel rotation speed, desired vehicle speed, and coefficient of the ground.

In [76], a hierarchical braking control was introduced and in its lower-level controller, a frequency-depended braking allocator was applied to distribute braking force into regenerative and friction brakes. The brake pedal travel with linear preset ratios was the input for the regenerative braking control strategy but a braking supervisor was used to switch to friction brake based on the wheels slip ratio and vehicle speed condition. The state of the charge and other characteristics relating to ESS were not considered in this paper. A three-level regenerative control strategy was introduced by [122], taking brake pedal, tire road adhesion, and SOC as input for the highest level. A multi-object optimization method was applied to balance the braking performance, regenerative braking loss efficiency, and battery loss in EVs with a front-wheel-drive system. It was reported that optimization objects presented a clear conflict, and they cannot be optimized at the same time. Another hierarchical regenerative braking control strategy by [71] targeted minimizing the aging of the battery alongside maximizing recovered energy and establishing a secure emergency brake in its up-level controller for a PHEV. A predictive model in this layer took the desired braking force which was calculated using pedal opening and a look table as main input and considering SOC, battery temperature and charging limit, and limitation of braking force in the EM. The control of EM for recovering the energy and pressure controller of the pneumatic brake were presented at the lower level. In [123] a parallel HEV with a two-layer control strategy was studied. The braking force distribution between the front and rear axle was calculated in the first layer regarding braking strength, the fuzzy controller with three inputs of SOC, vehicle speed, and braking strength was presented in the second layer to realize the coordinated control of mechanical braking.

To enhance overall vehicle efficiency, disabling regenerative braking below a low-speed boundary is crucial. Heydari et al. [124] utilized a dynamic detection of the low-speed boundary to shift the EM operating point,

improving energy recapturing capability in EVs. In their subsequent work, they aimed to maximize the recaptured energy through braking by considering the traction motor regenerative braking performance map [125]. Another study by Xu et al. [70] proposed a novel holistic series regenerative brake control strategy for a four-in-wheel motor EV. They optimized the allocation of brake torque based on factors such as SOC, the normal force on the tires, EM rotary velocity, and vehicle longitudinal velocity. Simulation results demonstrated enhanced energy recovery and improved regenerative braking efficiency. These findings contribute to the advancement of regenerative braking technology in electric vehicles.

Zhu et al. [77] introduced a regenerative braking strategy in a front-drive BEV that utilized multi-object optimization of a switched reluctance generator drive system. The aim was to enhance driving range, battery life, and braking comfort. The strategy considered vehicle speed, SOC, and brake pedal input to allocate regenerative and mechanical brakes effectively. A regenerative control strategy for a rear-driven minivan was discussed by [126]. A modified control strategy based on increasing the regenerative braking force on the rear wheels is introduced in this paper to increase recovered energy as the driver pushes the braking pedal. An optimized regenerative brake control strategy algorithm considering brake signal strength, SOC, and EM rotary speed was suggested by [127] to increase regenerated energy and vehicle stability.

5) REGENERATIVE BRAKING IN A CONVENTIONAL FCEV

FCEVs have fundamental differences from BEVs. Having a smaller-size battery and the presence of a fuel cell as the main power source need a complex energy management system. Unlike the BEV's battery, the smaller battery size of FCEV limits the amount of storable energy. The presence of FC is also a challenge. FC feeds the traction system mostly and in the event of braking, the battery might be fully charged. In this case, the vehicle is not able to store regenerated energy. Regenerative brake strategy in an FCEV appeared in a limited number of works and the majority of researchers have discussed regenerative braking in FCEVs in the context of energy management systems without further looking into brake control strategy. For instance, in [128], the energy management strategy for a FCEV with a hybrid ESS including battery and UC was studied. The control system considered SOC to select the battery or UC for storing energy of the brake. The system decides to charge UC if the battery is charged, But, the braking strategy and blending of friction and regenerative brake were not included. it seems the crucial link between energy management and regenerative braking needs more study. Discussing details of energy management systems is out of the scope of this article and we keep the focus on the energy recovery strategies implemented in the regenerative braking system.

The regenerative braking of a FCEV with a permanent magnet motor was presented in [129] and a UC was used

to capture braking energy. A fixed ratio was used to allocate the regenerative braking and friction braking with no safety or stability considerations. In [130], a regenerative braking control algorithm was introduced for an FCEV with a brake-by-wire system and regenerative braking on the front wheels. The input was the brake pedal signal, and the use of friction brakes was planned to accrue only when the deceleration demand was higher than a preset value. The negative effect of low speed on the regenerated energy and driving comfort was reduced by defining a weight factor. A fuel-cell hybrid electric bus with rear-wheel-drive was studied in [131]. A coordinated strategy of regenerative braking was applied to distribute force between regenerative braking force and mechanical braking force on the rear and front wheels considering the brake pedal travel. The fuel economy improvement was reported using this strategy compared to a bus without control strategy.

Designing regenerative brake control strategies alongside an energy management system, and evaluating it as a unified system, gives the opportunity to have a broad view of hydrogen consumption, vehicle safety and stability, and regeneration efficiency.

6) DRIVER BEHAVIOR IMPACT ON REGENERATIVE BRAKING

Driving style affects the energy consumption and vehicle range in electric vehicles [132], [133]. In a conventional EV or FCEV, the brake signal from the driver is the most important input for the braking strategy so the driving style also affects recovered energy. A four-year study on EVs showed aggressive driving increases specific energy consumption by 165 percent compared to passive driving [134]. The writers did not specify the rule of regenerative braking in this research. In another research, it was concluded that an aggressive driving style leads to more energy consumption but it results in a 220 percent higher potential for regenerative braking [135]. However, it was reported the increase in energy consumption is higher than the potential harvested energy. It was neglected that the capacity of ESS for storing the recovered energy is limited and the total amount of potential energy cannot be recovered. In [136] the effect of various driving pattern parameters, such as speed and acceleration, on the energy consumption of BEVs was studied. It was concluded that regenerative braking's ability to recover energy decreases the effects of most parameters. Improving driver behaviour effect on the energy efficiency of the EV can be studied on three levels: reports and feedback, driver-aware control strategies, and educating drivers.

Providing Reports and online feedback to the driver is regarded as a helpful approach to improving efficiency [137]. The optimal speed trajectory for an EV was studied in [138] and the authors suggested an eco-driving system to provide online assistance for drivers. A similar system to find the optimized speed profile and communicate with the driver using an interface was proposed in [139]. In [140], it was reported that displaying kinetic energy resources and energy

flow in HEVs could help the driver. The development of autonomous vehicles puts intelligent systems in charge of decision-making and planning and provides excellent opportunities to increase regenerated energy. In [141], it was shown that the energy consumption in an EV could drop by one-third as a result of giving driver feedback. They suggested a mobile application based on the concepts of echo driving to guide drives. The impact of driving style on energy efficiency has encouraged automakers such as Toyota to introduce an echo driving indicator in their products.

In addition to guiding the driver, it is also beneficial to develop driver-aware control strategies. The application of considering driver behaviour in vehicle control was discussed in [142], where a driver model predicts upcoming power demands applied to the energy management of series HEV. It seems that examining driver-aware brake control strategies and energy regeneration requires more attention.

Regarding an educational approach, drivers can be educated about tips and rules to gain higher recovered energy. For instance, in [143], directions for eco-driving are provided. Tips such as "brake gently" with a short description can help drivers adopt driving styles that increase regenerated brake energy. But even in highly motivated drivers for echo driving the difference is substantial and an efficient user-energy interaction is very helpful to guide the driver. The development of autonomous vehicles puts intelligent systems in charge of decision-making and planning and provides excellent opportunities to increase regenerated energy. So, with autonomous driving, there will be control over driving patterns and energy efficiency is likely to increase.

7) REGENERATIVE BRAKING IN AUTONOMOUS VEHICLES

Regenerative braking strategy in vehicles with autonomy level 3 and above which is referred to as autonomous EVs in this paper, will be reviewed in this section. Implementation of GPS and offline road maps alongside a fusion of sensors including radar, lidar, cameras, and ultrasonic sensors for real-time environment perceptions provide data beyond what a human driver can achieve. Furthermore, connectivity in vehicles such as vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) that results in connected and automated vehicles extend the potential of automated driving [144].

Since in autonomous vehicles, there is control over both acceleration and deceleration, the output of speed planning replaces the driver's brake pedal signal. The other type of using smart regenerative braking is by automating only the brake in the car-following scenarios which will be covered in this paper. The focus in autonomous vehicle studies has been on energy-efficient driving strategies and eco-driving strategies to reach the optimal speed and acceleration to decrease energy consumption. In [36], it is shown that to travel between two stop points the most efficient way is to accelerate with maximum power and then coast with no brake to stop. However, coasting is not possible or safe in all situations [35], especially in urban areas. Based on our

review many researchers have overlooked the capability of regenerative braking to recover energy in intelligent EVs or FCEVs and its potential and limits are neglected.

Regenerative braking limitations, such as the maximum regenerative braking capability and the inability to harvest mechanical energy at very low speeds, were discussed in a study on eco-driving by Mohammadi et al. [145]. A car following a control strategy for an intelligent BEV was proposed by [146] including a regenerative braking strategy to increase energy efficiency and safety. The proposed adaptive cruise control framework had two levels and the brake intensity was calculated based on the desired acceleration which was the output of a higher level. In the lower-level controller, by considering the available regenerative power and adhesion coefficient, a braking strategy was developed.

In [147], a car-following scenario was proposed with manual acceleration and a smart regenerative system for BEV. The applied deceleration planning in this research takes the accelerator pedal position, brake pedal position, acceleration, velocity, relative distance, and relative velocity as inputs to calculate a reference deceleration. This acceleration command results in the torque output of an acceleration controller and a feedback-and-feedforward controller. In [148], a front-wheel drive BEV with an ultracapacitor as an auxiliary power source was the subject of a study for optimal speed planning. The brake force is distributed between the rear and front wheel and a fuzzy controller with three inputs of SOC of UC, brake intensity, and vehicle speed, generates the regenerative brake force coefficient like a conventional vehicle. Since it is a connected and automated vehicle, signal light status, and timing information from infrastructure are considered constraints for optimization speed trajectory at the signalized intersection.

In [149], a smart regenerative brake was developed for autonomous vehicles to take control of deceleration situations without the driver's intervention. After determining the driving state, a reinforcement learning algorithm manages the output desired acceleration by considering two deceleration planning. The driving data used for this approach were driver acceleration and brake pedal input, vehicle speed and acceleration, preceding vehicle speed, relative distance, EM torque, and EM speed.

In [150], the limitation of low-speed regenerative braking, maximum braking force available on the axle with regenerative braking, and maximum charging current was considered for optimized speed planning for an autonomous and connected EV in a signalized roadway with intersections.

In [151], a speed planning algorithm for the rule of driving assistance system or part of autonomous vehicle control was proposed. It was assumed that the intersection traffic data is collected by V2I and an optimized speed planning algorithm, based on information was applied to increase energy recovery and drive comfort. A genetic-based eco-driving technique was studied by [152], putting regenerative braking into account. In [69], an optimal deceleration planning system was presented for connected and automated

electrified vehicles facing an upcoming deceleration event. The inputs of deceleration planning were initial speed, final speed, residual distance, and required time. The objective of the optimal control problem was to maximize regenerative braking energy apprising the regenerative power limit of EM. For the deceleration, vehicle dynamics and forces were taken into account.

When a driver is in charge of controlling a vehicle, acceleration commands are the inputs of the regenerative braking strategy. The driver can be guided to use pedals more efficiently, but it is still a challenge to obtain the best inputs. In the autonomous vehicle, there is a chance to look one step back and calculate the best acceleration or deceleration commands. Then, the optimized speed would be the input for the braking strategy to guarantee the vehicle's safety and stability. This shows the great potential to increase energy efficiency in autonomous vehicles.

Connected and automated fuel cell hybrid electric vehicles (CAFHEVs) represent the next generation of FC-based road transport. Recent studies have focused on co-optimization by merging speed planning and EMS to enhance the performance of these vehicles. This method involves calculating the optimal speed at the upper level and optimizing the EMS based on the calculated speed. In a study by Jinquan et al [153] a co-optimization fuel cell bus with regenerative braking was studied to reduce hydrogen consumption. The upper level used dynamic programming for speed planning on the road with intersections and the lower level used MPC for the EMS. The computation time and load in the co-optimization problems is an important factor and in [154] a bi-level convex co-optimization method for a CAFHEV was suggested in this regard. Authors reported improved computational time, but the effect of regenerative brake was not discussed. In [155] another method to reduce the complexity of co-optimization was introduced and in the speed planning layer, the limits of EM to regenerate energy on a sloped road were taken into account. Authors in [156] proposed a co-optimization for the intelligent FCHEV. The work was continued in [157] by considering regenerative brake and the urban traffic setting, followed by another study [158] with considering dynamic road curve. In [159] and [160] the studies for the co-optimization did not include the effect of regenerative braking on the upper layer speed planner.

Despite the differences between FCEVs and other types of EVs, research on autonomous FCHEVs is very limited. In addition, using perception and online detection approaches while considering regenerative braking applications has emerged in a limited number of studies.

C. REGULATIONS AND STANDARDS ON REGENERATIVE BRAKING

It is important to note commercial application regenerative braking systems must undergo rigorous tests and meet safety and stability standards. These regulations and standards aim

to ensure the proper functioning, efficiency, and safety of regenerative braking technology (as a part of the vehicle braking system), including aspects like energy recovery, braking performance, electromagnetic compatibility, system integration, and adherence to environmental and safety regulations. While covering all the regulations on braking in a study is not feasible, the safety measures could be vital as they may directly affect the regenerated energy.

The majority of studies have limited their study to the energy efficiency aspect of regenerative braking without considering regulations and related standards, while some studies have ensured that the braking strategy complies with regulations. There are several standards available related to braking such as FMVSS 135, ECE R13, and ISO 6469. ECE R13, also known as Regulation No. 13 of the United Nations Economic Commission for Europe (UNECE), is a worldwide accepted standard that specifies uniform provisions concerning the braking system of motor vehicles. This regulation is acknowledged as a valid braking standard under the 1958 agreement and is adhered to by all United Nations (UN) members, including Australia, Austria, Japan, Germany, Italy, Switzerland, Norway, the Russian Federation, the United Kingdom (UK), and the United States of America (USA) [118].

Among reviewed references, all the works that considered compatibility with a standard considered, have used ECE R13 [106], [113], [117], [118], [122] [77], [123] [126], [127] [146]. The Chinese GB/T B594-2033 regulation was used by one reference [131].

IV. ENERGY HARVESTING FROM SUSPENSION SYSTEMS

When a vehicle moves on a road there is a chance to harvest vertical vibrations caused by uneven roads and convert them into electrical energy. Traditionally shock absorbers in parallel with suspension springs are applied to decrease vibration by dissipating that energy as heat but a regenerative suspension system (RSS) provides a prospect to harvest vertical vibrations [161], [162]. Fig.12 shows the general idea of an RSS. When a vehicle crosses the road, there is linear movement in the suspension system. This movement is used to produce electricity in a direct or indirect approach. Finally, the electricity is stored in an ESS. A typical mid-sized passenger car there is the potential to harvest energy ranging from 100 W to 400 W on a good road with approximately 96 Km/h [161]. This harvesting approach has been studied by many researchers before, both on conventional and electric vehicles, but it was reported to be more effective in HEVs and EVs [163]. The fuel improvement for a conventional passenger car with regenerative suspension was reported to be between 2 to 3 percent while numbers for the EVs vary between 7 to 10 percent. The suspension system of an EV and a conventional vehicle could be the same (despite some topologies such as in-wheel-motor). Still, it should be noted that EVs have a proper ESS to store any regenerated energy, but when it comes to conventional vehicles the storage and use of it should be considered.

The harvested energy in a conventional vehicle should come alongside an auxiliary ESS or the energy must be directed to feed auxiliary devices. In this paper, we did not limit the review on RSS to works that have expressed EVs as the main target of their study.

It should be noted that potential harvestable power in literature has been reported in a very wide range and these results may suffer from using a simple quarter-car model, using tire-road point contact model, and testing on the simulated road that is too rough in comparison with the real roads [164]. The dissipated instant power by a passive suspension system can be calculated according to [165]:

$$P_i(t) = F_d (\dot{Z}_s(t) - \dot{Z}_u(t)) = C (\dot{Z}_s(t) - \dot{Z}_u(t))^2 \quad (8)$$

The instant power denoted as P_i is determined by the multiplication of the damping force F_d and the suspension velocity denoted as $\dot{Z}_s(t) - \dot{Z}_u(t)$. C represents the damping coefficient.

The equation gives a basic idea of dissipated energy, however, the regenerated energy depends on the implemented method. The regenerated energy in the suspension system depends on four basic factors depending on the vehicle or the road [166]:

A. THE CONDITION OF THE ROAD AND ITS ROUGHNESS

the oscillation created on a very plane surface does not create considerable vibration, hence bumpy roadways are more suitable for the regenerative suspension system (RSS). In [167], an energy recovery system for a mild HEV including regenerative suspension was studied. A linear motor was used to harvest vibration. The harvested energy on the C-class road was considerably higher than on A-class roads.

B. VEHICLE MOVING SPEED

In [168], it was shown that a higher traveling speed of a vehicle results in higher harvested energy.

C. DAMPING AND STIFFNESS OF THE TIRE AND SUSPENSION

The power in the vehicles' suspension depends on tire stiffness, the higher stiffness in the wheel results in higher regenerative power. On the other hand, ride comfort is affected by suspension stiffness [161].

D. THE LOAD OF THE VEHICLE

In heavier vehicles such as trucks and buses, there is higher vibration intensity.

The suspension of a vehicle can be classified as passive, semi-active, and active. Because of reliability and the simple structure, most vehicles are equipped with passive suspension [169]. In the passive suspension, the harvested energy will be stored to be used based on vehicle demand. Since semi-active and active suspension uses power to deliver more riding comfort, the harvested energy can be used as a means to reduce their energy demand.

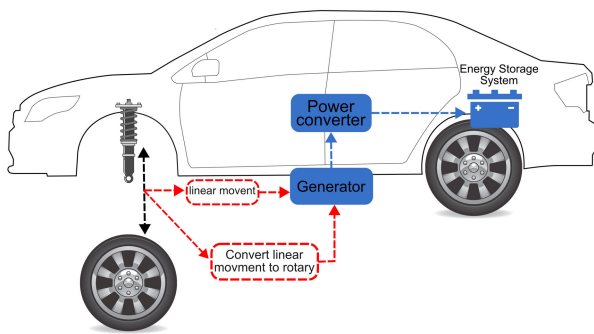


FIGURE 13. The scheme of RSS.

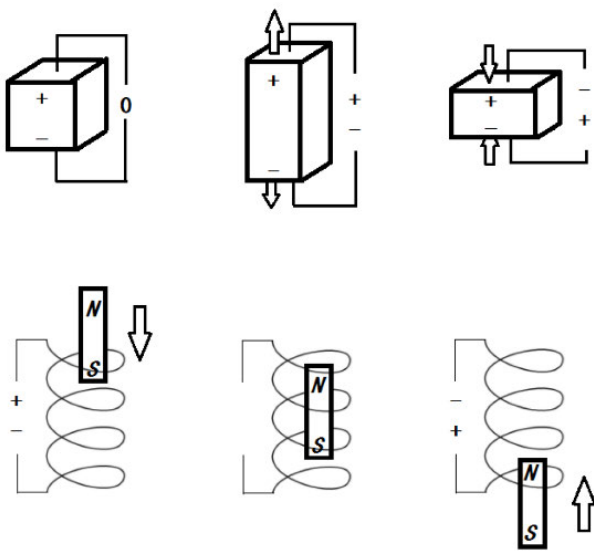


FIGURE 14. Piezoelectric (up) and electromagnetic (down) regeneration [170].

E. ENERGY HARVESTING IN PASSIVE SUSPENSION SYSTEMS

There are three approaches to harvesting mechanical energy and vibration: a piezoelectric transducer, an electromagnetic transducer, and an electrostatic transducer. The first two methods have been applied and tested in numerous studies. Fig.14 shows the basic scheme of piezoelectric and electromagnetic regeneration.

In general, piezoelectric offers power density, compact size, and ease of use, but electromagnetic transducers outperform them in terms of a lower strain, low resonant frequency, and higher displacement. The last factor is very important since there is a maximum displacement of 10 cm in passenger vehicles. Regarding these differences, electromagnetic-based RSS has attracted more studies [166].

The electromagnetic regenerative suspension includes direct (linear) and indirect (rotary) types. In a direct setup, the shock absorber’s cylinder contains permanent magnets and coils. It produces electricity when a relative linear movement between coils and magnets happens. The basic design suffers from limited damping and limited power density, and studies

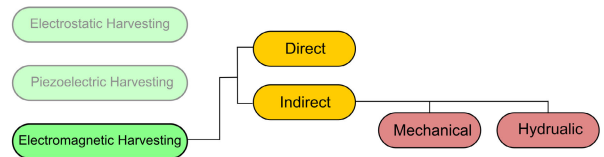


FIGURE 15. Classification of electromagnetic-based harvesting.

have suggested the use of parallel hydraulic damper and considering new designs to address these shortcomings [171]. The indirect type needs a mechanical or hydraulic mechanism to convert the linear motion to a unidirectional rotary motion with desirable velocity and then uses a DC generator to produce electricity. Mechanical mechanisms such as rack and pinion, ball screws, and algebraic screws have been mentioned in the literature. The indirect type suffers from energy loss due to friction in the complicated mechanism [172]. Fig.15 shows the classification of electromagnetic-based suspension systems.

In [173], a half-scale prototype of a direct actuator generated 16-64 W of power. Another study [174] introduced a direct electromagnetic energy harvester with four configurations, achieving 2.8 W at 0.11 m/s. For range-extended EVs, [175] proposed an indirect mechanical RSS with dual-overrunning clutches, yielding 44.24 percent efficiency and 4.302 W power output. [176] presented a non-contact piezo-magneto harvester, with regenerative power ranging from 16 W to 242 W at 120 km/h. In [177], a twin ball screw mechanism achieved 36.4 percent efficiency and 3.701 W output power at 1 Hz frequency and 3 mm amplitude. To address issues with traditional mechanisms, [178] proposed an algebraic screw linkage mechanism. [179] studied a double-sided arm-toothed indirect RSS for semi-trailer trucks, obtaining power levels of 0.33 W, 1.33 W, 5.24 W, and 21.3 W for road classes A, B, C, and D respectively. In [180], a linear electromagnetic generator-based RSS provided continuous power regardless of position or speed, with 39.46 percent efficiency at 2.5 Hz and 7 mm amplitude. Additionally, [181] proposed a mechanical electromagnetic harvester using helical gears and dual tapered roller clutches, achieving 40 percent efficiency and 270 W power output at 2.5 Hz and 5 mm amplitude.

An autonomous new energy bus was the subject of a study to regenerate energy from vibration on the road [182]. The autonomous bus could benefit from 17 W regenerated power which was enough to feed a LIDAR for 323 days. EVs with in-wheel motors have larger unsprung mass in their suspension and this results in more discomfort and safety on uneven roads [183]. In [184] writers in the search for a regenerative suspension suitable for the setups of in-wheel electric vehicles investigated a suspension system embedded with an electromagnetic-tuned mass damper (TMD). The results of the simulation on the 11 DOF model of the vehicle indicated a maximum RMS power of 58 W at 30 m/s and on a D-class road.

The design method of the hydro-magneto-electric regenerative shock absorber was reported in [185] to increase ride comfort in parallel with harvesting energy. The design included a hydraulic cylinder-tube system, gear system, hydraulic motor, and electric generator. The measured power output of the prototype was between 7 W to 14 W (with an input frequency of 1 and 1.5 respectively), smaller than the maximum of 18 W in the simulation. A hydraulic integrated interconnected regenerative suspension was studied in [186]. It was shown with a half-car model that an off-road vehicle on a C-class road at the speed of 72 K/h can harvest the power of 417.40 W. A compact design of an electro-hydraulic system was suggested in [187]. The highest regenerative power of 75 W was obtained in the hard-driving tests compared to 5 W in normal-driving tests. Bench test results for another electro-hydraulic interconnected RSS indicated a potential of harvest 525 W at the speed of 8 Km/h on a D-class road for an SUV [188]. To increase the safety of the vehicle an electromagnetic harvester co-existing with a conventional passive shock absorber was introduced [189]. The test results of the prototype showed power output ranging from 0.64 W to 1.08 W at the frequency of 10 Hz and amplitude of 2 mm.

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A piezoelectric energy harvester for an electric truck was designed [191] and the RMS of harvested power was reported to be 18.83 W. The maximum of 102.24 W was obtained on a pulse road drive at the speed of 30 km/h. A mathematical model for dual mass piezoelectric bar harvest was developed by [192], and for specific material and geometry parameters, the possibility of harvesting 738 W was announced. Simulation outcome of another piezo harvester in parallel with the conventional suspension system calculated 322.4 W of regenerative power [193].

F. ENERGY HARVESTING IN SEMI-ACTIVE AND ACTIVE SUSPENSION SYSTEMS

Active suspension needs considerable energy to run which is a barrier to widespread use of it [161] and regenerative active suspension provides the opportunity to act as a partly self-powered damper that offers better ridding and road handling [165]. The idea of using regenerative active suspension in HEV was investigated [194], and based on the simulation results the fuel economy will improve with this method. Fig. 16 illustrates a basic quarter model of an active suspension system with a regenerative force actuator. The Z_s and Z_u are the vertical displacements of the sprung mass and un-sprung mass respectively, and Z_r is road excitation. m_s represents the varying sprung mass, and m_u refers to the un-sprung mass. k_t is the tire damping coefficient and c_t stands for the damping coefficient of the tire. The actuator force is represented with U . The equations of vertical motion can be

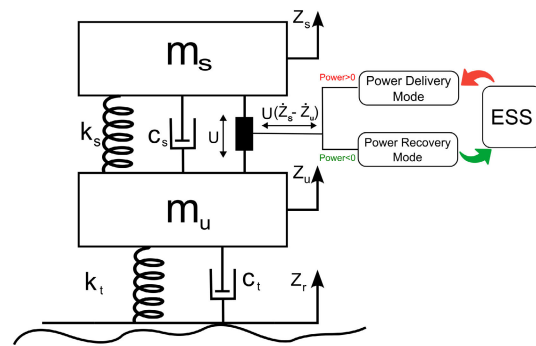


FIGURE 16. 2-DOF quarter model of the regenerative active suspension system.

described as follows [195]:

$$m_s(t)\ddot{Z}_s(t) = k_s (Z_s(t) - Z_u(t)) - C_s (\dot{Z}_s(t) - \dot{Z}_u(t)) + U(t) \quad (9)$$

$$m_u(t)\ddot{Z}_u(t) = k_s (Z_s(t) - Z_u(t)) + C_s (\dot{Z}_s(t) - \dot{Z}_u(t)) - k_t \times (Z_u(t) - Z_r(t)) - C_t (\dot{Z}_u(t) - \dot{Z}_r(t)) + U(t) \quad (10)$$

And the active suspension power, P_{AS} , is calculated as:

$$P_{AS} = U(\dot{Z}_s - \dot{Z}_u) \quad (11)$$

When the system is working in the power recovery mode the power is negative and the regenerated energy could be delivered to ESS. In [196], a semi-active regenerative suspension with an adjustable shock absorber and a linear motor was introduced. The system contained a UC to store generated energy and the motor was capable of controlled damping resulting in 15 percent improved riding comfort. A series of tests on an electro-hydraulic semi-active damper prototype for off-road vehicles [197] resulted in an average of 110.6 W regenerative power.

In [190], a regenerative active suspension applied on an in-wheel motor-driven BEV was introduced with dual actuators to increase comfort. Based on the road type used for the test, the regenerated energy ranged between 4.9 W to 45 W. An ESS including an onboard low-voltage battery pack and a UC was proposed to increase the harvesting efficiency. Another study of in-wheel EVs was in [183] and an unmanned ground vehicle (UGV) with active electromagnetic suspension was proposed. Based on the simulation the system was able to regenerate 10 W on a B-class road at high speed. Table 4 reports the references that have considered applying the suggested RSS in an EV.

Regarding the harvestable output power, it will be the same for any type of vehicle with the same weight and RSS and from the same class, so it seems not necessary to conduct different research for FCEVs. That might be the reason for the lack of studies (to the best of our knowledge) on RSS in FCEVs. The only notable point to consider is the weight of FCEVs, which tends to be slightly higher compared to same-class HEVs and BEVs. For example, the

TABLE 4. References that have considered the application of proposed RSS in an EV.

No.	References	Vehicle type	Energy Harvesting Technology	Road Disturbance	Regenerated Power (Total)
1	[183]	In-wheel Motor BEV	Active Direct Electromagnetic	Road Class B	10 W
2	[190]	In-wheel Motor BEV	Active Indirect Electromagnetic	Road Class C	4*(49.2) W
3	[182]	Electric Bus	Passive Indirect Electromagnetic	2.5 Hz with 7 mm Amplitude	4*(4.25) W
4	[184]	In-wheel Motor BEV	Passive Direct Electromagnetic	Road Class D	58 W
5	[181]	Not Specified	Passive Indirect Electromagnetic	2.5 HZ with 5 mm Amplitude	270 W
6	[175]	PHEV	Passive Indirect Electromagnetic	2.5 Hz with 7.5 mm Amplitude	4*(4.302) W
7	[177]	PHEV	Passive Indirect Electromagnetic	1 Hz with 3 mm Amplitude	4*(3.701) W
8	[176]	Not Specified	Piezoelectric Energy Harvester	Road Class E	242 W

Toyota Mirai is approximately 300 kg heavier than the Tesla Model 3. As discussed, heavier weight can contribute to a higher amount of harvested energy. In addition, there was no research including a field test of RSS in FCEV in the literature.

V. OTHER SOURCES FOR ENERGY HARVESTING

There are other minor opportunities to harvest energy in a BEV or FCEV, and recovered energy can be stored or used for running sensors and electrical devices. In this section, we will review these methods that have not been widely studied. Some of the works are not proposed exclusively for EVs and are applicable in any type of vehicle, but because an EV always comes with an ESS, it is simpler to apply these works to an EV. Considering the nature of these methods, which are independent of the drivetrain and do not exert additional pressure on the energy storage system (ESS), their application to FCEVs and EVs is generally similar in most cases.

A. HARVESTING HEAT AND BODY VIBRATION

HEVs have ICs to run alongside an EM and in the IC engine there is considerable energy loss. Recovering heat energy in IC engine have been studied and reviewed in many works [52], [198], [199], [200], and the nature of the current paper is not circling around HEVs, so this part is not covered in the present paper. Regarding other heat sources in [201], recovering heat from brake disks using a thermoelectric generator was proposed, and based on the simulation results, 4 W of harvested energy is available at a minimum.

Other than regenerating energy in the suspension system the opportunities to harvest energy from general body vibration or the energy during steering have been studied in the literature. In [202], the design of a piezoelectric harvester to recapture energy from an autonomous vehicle's vibration was presented and tested. A hybrid kinetic energy harvester (KEH) for an autonomous bus was presented in [203]. The KEH harvests inertial kinetic energy during accelerating and turning in the vehicle using a small generator and piezoelectric beam in an uneven table and base (Fig.17).

The highest power out of the KEH was 8.31 mW at 8 m/s² acceleration and it is capable of powering 54 LED lights.

B. ENERGY HARVESTING FROM WHEELS AND TIRES

In driving a vehicle, the rolling speed of the tire changes, and the tires are under load. Considering this situation there is a harvesting potential by implementing triboelectric and piezoelectric harvesters [204]. The harvested energy from the tires can be used to power pressure and speed sensors on the wheel [205] offering no need for battery replacement and longer durability.

In [206], it was estimated that more than 1 kW of energy wastes as the pneumatic tire in a passenger car deflects and the authors presented a piezoelectric harvester, capable of recovering 42 mW. Another piezoelectric harvester was studied in [207] to act as a power source for strain sensing and wireless data transfer. The recovered energy was sufficient to feed 78 LED lights. A rainbow-shape piezoelectric material layer for mounting on the internal side of a pneumatic tire was proposed in [208] and simulation data indicated 5.85 mW harvesting power is achievable.

To monitor the pressure of a tire, a triboelectric nanogenerator was proposed in [209]. The harvested power of 22.3 mW was reported at the speed of 100 rpm. A hexagonal-shaped triboelectric harvester was suggested in [210] to power a wireless tire pressure sensor (Fig.18). It was reported that applying 500 units of this harvester to a standard tire at the speed of 100 km/h would result in 1.2 W recovered power.

In some references, the implementation of energy harvesters on the wheel (rim-mounted harvesters) has been presented. In [211], a piezoelectric harvester with the application of stochastic resonance was attached to the wheel. The mechanism included piezoelectric film and a magnet shown in Fig.19. Another wheel-attached piezo harvester was proposed in [212] for an intelligent vehicle wheel system with sensors inside such as temperature, pressure, deformation, and torque sensors. The design was capable of harvesting between 0.61 to 6.28 mW at speeds of 40 to 120 km/h. A weighted pendulum was studied in [213] to recapture energy from a rotating wheel with the pick converted power

Electric Driverless Bus



KEH

Uneven Turntable

Base

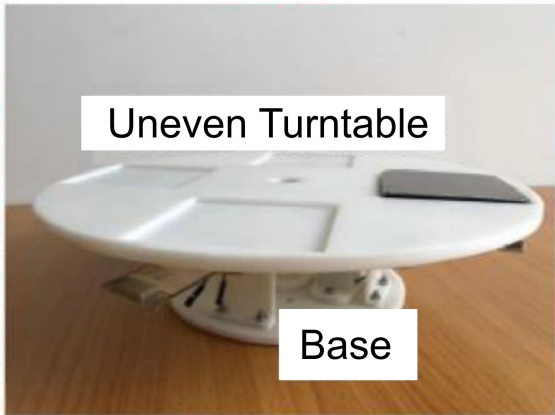


FIGURE 17. KEH energy harvester [202].

of 0.9-2.6 mW. The authors reported approximately 0.2 to 0.3 mW of harvested energy from the physical model in [214].

C. WIND ENERGY HARVESTING

As was shown before, based on the drive cycle between 30 to 47 percent of the energy directed to the wheels is lost due to wind resistance. One solution to this problem is to optimize the aerodynamic design of the vehicle, which has been studied comprehensively before and is beyond the frames of this paper. In some references, the application of a vehicle-mounted wind turbine (VMWT) has been investigated [215], [216], [217], but since the VMWT has weight and increases the drag force, it reduces vehicle efficiency. So, reporting the power produced by VMWT without considering the drop in vehicle efficiency is misleading, and it might be the case in [34].

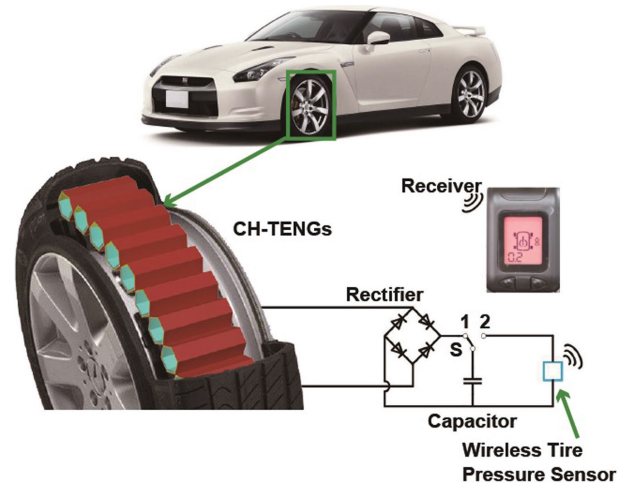


FIGURE 18. Energy harvesting from the tire [210].

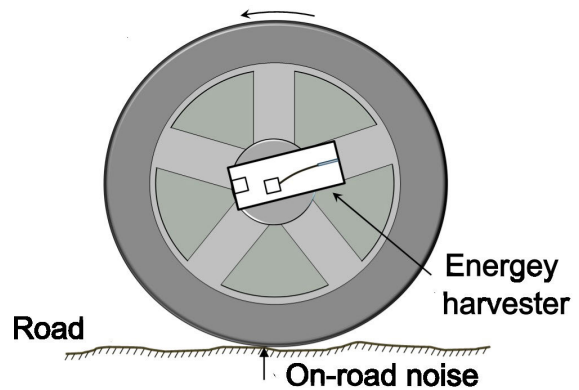


FIGURE 19. Rim-mounted energy harvester [211].

In [218], a flutter piezo-electromagnetic hybrid harvesting structure was proposed to recover wind and vibration during vehicle movement. Its structure included a piezoelectric beam with a tip magnet, a rigid airfoil, and an electromagnetic harvester fixed in front of the airfoil. The experimental result showed the harvested power of 14.5 mW in the piezo harvester and 31.8 mW in the electromagnetic harvester at the wind speed of 18 m/s.

D. SOLAR ENERGY HARVESTING

Harvesting solar energy and converting it into electricity for different applications has been studied for many years and with the current market trend in the price of photovoltaic (PV) modules, solar-powered EVs (PVHEV) is getting more serious attention [219]. However, with the current efficiency of available PV panels, even at midday with the highest sunlight profile, the PVHEV with the 8 m² PV panel can generate a maximum of 11 horsepower [220]. Hence, considering EVs with commonly over 100 kW traction EMs, a full solar electric vehicle is not practical, but Hybrid solar vehicles are beneficial [221]. The roof of the vehicle as the

main space to apply solar panel needs should be designed with proper geometry and a moving solar roof increases harvested solar power in most cases [222]. Non-uniformity of solar irradiation and changes in temperature also affect PV efficiency and are a challenge for this type of HEV [223].

The contribution of applying solar panels to increase the travel distance of EVs was discussed in [224] and a significant increase in the driving range on urban roads was reported. An off-road solar-powered electric vehicle was designed in [225]. The increase in vehicle range and lower carbon footprint were reported as pros of the design. A battery/PV/wind hybrid power vehicle with a 19.2 kWh Li-ion battery was proposed in [226] and authors reported a 19.6 km extended range for a PHEV. The application of solar harvesting alongside regenerative braking in a through-the-road HEV was studied in [227]. Hybrid vehicles have the capability to utilize a combination of fuel cells, batteries, and solar panels as simultaneous energy sources. The modeling and simulation of HEV in MATLAB Simulink with FC, battery, and solar panels were presented in [228]. A hybrid vehicle with an integrated energy system including fuel cells and PV was studied in [229]. The proposed HEV was compared with an FCHEV without the solar panel and the use of PV resulted in less fuel cell destruction. In [230] a Zero-Fuel-Zero-Emission (ZFZE) electric vehicle with FC, PV panels, and wind turbine was introduced. Based on the simulation the authors reported a travel distance of 260km in 4.7 hours. However, the study did not include the analysis of optimal energy management.

Overall, PVHEVs are in the developing phase with clear advantages, and with future development and progress, they might gain more market share as the PV panel gets cheaper and their efficiency is increased. Utilizing advanced look-ahead techniques is required to tune the energy management and control for maximizing the harvested energy from the panels [231]. Solar charging stations are another solution to power electric vehicles with clean energy that shifts the harvesting unit from the vehicle to the infrastructure [232].

E. RADIO FREQUENCY ENERGY HARVESTING

Electromagnetic waves offer diverse opportunities for energy harvesting, including visible light, ultraviolet rays, and more. One notable application is the conversion of radio waves into direct current (DC) power. A prime example of this is radio frequency identification (RFID) tags, which exemplify a straightforward utilization of this technology [233]. There are two approaches to RF energy harvesting. First, it can be obtained from dedicated sources that are intended for this specific application. The roadside charging units can be connected to the existing power grid, allowing them to draw electricity from conventional sources. Alternatively, they can be integrated with renewable energy systems, such as solar panels, enabling the use of clean and sustainable energy. This versatility makes roadside charging units a practical solution for providing electric vehicle charging infrastructure

in remote and environmentally conscious areas. Exploring the subject of wireless charging falls outside the scope of this paper but can be further investigated, particularly within the area of wireless charging technologies. In the second approach, the focus is on harvesting ambient RF signals for energy harvesting. These signals, which include transmissions from TV and radio towers, are primarily intended for other applications. However, they can still serve as valuable sources of energy that can be harvested and utilized for various purposes [234], [235]. The ambient RF energy harvesting is promising, particularly in urban areas characterized by a high density of radio waves.

RF energy harvesting has the potential to supply energy for low-power applications in EVs as well as other forms of transportation, such as unmanned aerial vehicles (UAVs). However, ambient sources have some disadvantages, for instance, low energy density [236]. RF energy harvesting has been a subject of investigation in numerous studies, including research on simultaneous wireless information and power transfer (SWIPT) [237], [238], [239]. However, its specific application for electric and autonomous vehicles has not been extensively studied and comprehensively explored.

VI. FUTURE TRENDS AND RESEARCH GAPS

Research on energy harvesting and recovery methods presents a valuable opportunity for automakers to improve the energy efficiency of vehicles available on the market. By exploring and implementing these innovative methods, automakers have the potential to revolutionize the way vehicles utilize and conserve energy. In fact, several energy harvesting and recovery methods have already found their way into vehicles that are currently available in the market. These methods are highlighted in Table 5, which provides a comparative analysis of different vehicle models and their energy recovery capabilities. One notable example of such technology is regenerative braking, which has been successfully integrated into EVs for a long time. While regenerative braking has become a standard feature in many EVs, it is important to note that information regarding the maximum regenerative braking capacity is not always readily available for every product on the market. As mentioned earlier, it is important to consider that energy recovery is influenced by a multitude of factors. Consequently, the energy numbers presented in Table 5 may vary across different situations and conditions.

In the previous sections, this paper reviewed energy loss in a vehicle, the architecture of FEVs, energy harvesting potentials in BEVs and FCEVs from different sources, and various opportunities to recover energy in conventional or autonomous vehicles. Based on this analysis multiple suggestions and challenges are presented in the following.

A. REGENERATIVE BRAKING IN AUTONOMOUS ELECTRIC VEHICLES

Many references have worked on the increased energy recovery as the driver pushes the brake pedal but when it

TABLE 5. Examples of energy recovery and harvesting in commercial EVs.

Method	Vehicle Type	Brand and Model	Recovered or Harvested Energy or Its Equivalent	Reference
Solar Harvesting	HEV	Hyundai Sonata Hybrid	The annual range can be increased up to 1300 km	[240]
	BEV	Aptera	700 W of continuous charging power	[241]
	HEV	Karma GS-6	200 W of power from roof panel	[242]
Regenerative Braking	BEV	Audi e-tron	a maximum of 220 kW at a speed of 100 km/h	[243]
	BEV	Porsche Taycan	up to 275 kW	[244]
	BEV	Tesla (3, Y, S)	N/A	[245]
	HEV	Toyota Prius	N/A	[246]
	BEV	Volkswagen Id.Buzz pro	up to 100 kW	[247]
	BEV	KIA EV6 GT	Peaks at over 300 kW recuperation	[248]

TABLE 6. Recent publications on co-optimization in FCEVs.

Reference	Publishing year	Methods used in co-optimization	Driving scenario	Test
[153]	2021	DP + MPC	Two intersections, with and without other vehicles	Hardware in the loop (VTSsystem)
[154]	2022	MOSEK solver + ADMM algorithm	Signalized intersections	MATLAB
[156]	2022	Gradient-based MPC + MPC	Sloped road with other vehicles	MATLAB
[159]	2022	MPC	Simulated traffic situation	VISSIM
[160]	2022	Constraint stochastic MPC	Simulated traffic situation	VISSIM
[157]	2022	Gradient-based MPC + MPC	Sloped road with a traffic light and speed limit	MATLAB
[155]	2022	DP + PNP	Sloped road	MATLAB
[158]	2023	Gradient-based MPC + PRA-ECMS	Road with dynamic curve	MATLAB

comes to autonomous vehicles the focus is on optimized speed planning without considering regenerative braking. The potential of regenerative braking during autonomous navigation has been overlooked in most cases by researchers. In addition, in real-world situations, the driving process gets interrupted by different unpredicted events such as pedestrians or other vehicles' maneuvers, and considering only stop signs and traffic lights for regenerative braking is not enough. The information from LIDAR, cameras, radar, and other sensors can be utilized not only to conduct safe braking but also to optimize the recovered energy through regenerative braking. Based on echo-driving principles, it is better to limit braking situations, but relying only on coasting is not safe and practical. Using look-ahead technologies and long-term road anticipation can

be employed to improve energy efficiency in an EV in braking events.

B. REGENERATIVE BRAKING IN FUEL CELL ELECTRIC VEHICLES

Based on our current knowledge, there is a limited number of studies available on regenerative braking in fuel cell electric vehicles (FCEVs), particularly in the context of autonomous FCEVs. One area of focus that scholars have been exploring is co-optimization. Table 6 provides a compilation of recent studies conducted on this topic and Highlights co-optimization in CAFHEVs as the emerging trend. However, the mentioned studies in Table 6 do not investigate the potential of switching between battery and FC before braking in terms of increasing recovered

TABLE 7. Effects of vehicle and environment parameters on main Energy harvesting and energy recovery methods.

Method	Vehicles Factors	Environment
Regenerative Brake	<ul style="list-style-type: none"> Higher speeds and weight result in higher harvestable energy EM capacity to regenerate electricity bounds the regenerated power The ESS type greatly impacts storing the recovered energy. 	<ul style="list-style-type: none"> Urban traffic is more suitable Aggressive driving results in more regenerated energy
Regenerative Suspension	<ul style="list-style-type: none"> Higher traveling speed of the vehicle results in higher harvested energy In heavier vehicles such as trucks regenerative suspension energy is higher 	<ul style="list-style-type: none"> Bumpy roadways are more suitable for regenerative suspension systems
Solar Harvesting	<ul style="list-style-type: none"> With a more overall dimension of the vehicle and subsequently solar panels, energy harvesting increases. 	<ul style="list-style-type: none"> Depends on the available sunlight
RF Harvesting	<ul style="list-style-type: none"> Speed and direction of the vehicle can effect signal strength 	<ul style="list-style-type: none"> Ambient FR harvesting is more suitable for urban areas In rural areas, the distance from dedicated sources is important
Rim and Tire Energy Harvesting	<ul style="list-style-type: none"> Based on the design, it can be affected by, speed, change of speed, and wheel weight 	<ul style="list-style-type: none"> Road roughness can affect the system.

energy. By taking into account the fundamental differences between BEVs and FCEVs, The battery in the FCEV has a lower capacity compared to BEV. Regenerated energy from braking, must be stored in ESS and the smaller battery limits its capacity. Because recovering the energy while it cannot be stored in ESS is pointless. Therefore, further research on co-optimization in CAFHEVs to maximize regenerative braking and improve efficiency presents an interesting area of study. The presence of The FC is an important factor. Using look-ahead data can be used to optimize hydrogen usage as the vehicle can rely on upcoming braking events. In Autonomous FCEV, with the data of upcoming braking events, the FC can be switched off to save fuel. With running on the battery pack, the vehicle can harvest more energy. Since the battery pack will be charged at a predicted point, the vehicle is able to switch from hydrogen to battery. In the next steps, the impact of this approach alongside other factors such as FC health could be investigated. The low temperature in winter affects the capacity of some battery types and this is more important in FCEV with smaller batteries. considering winter conditions in regenerative braking strategies can improve efficiency. Brake strategies for the winter conditions, and using extra harvested energy to heat the battery pack can be investigated in future studies.

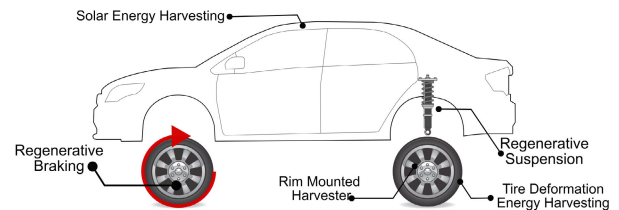


FIGURE 20. Multi-source energy harvesting.

C. FUSION OF ENERGY HARVESTING APPROACHES

There are a considerable number of works on RSS, but the number of studies with long-term field test results is limited. The harvesting potential of RSS is lower than regenerative braking. Other methods that were discussed in this paper also have a limited capacity to harvest or recover energy. However, in smart vehicles with varieties of sensors and onboard electronics, every opportunity to increase efficiency should be considered. In this case, applying and operating different harvesting approaches in the vehicle at the same time could be the right spot to conduct more research (Fig. 20). Further research is needed to explore the simultaneous application of multiple energy recovery methods in electric vehicles. While certain methods, such

as solar energy harvesting and regenerative braking, have been commercially implemented [241], the effectiveness and feasibility of combining these techniques with others require in-depth investigation. Specific investigations into the co-existence of different energy recovery methods would greatly contribute to maximizing energy efficiency and optimizing the overall performance of electric vehicles.

VII. CONCLUSION

Harvesting and recovering energy is an effective approach to extending the range, decreasing fuel consumption, and facilitating the market expansion of BEVs and FCEVs. Different parameters from vehicles and also the environment can affect these harvesting and recovering methods which are presented in Table 7. In the presented review, the energy loss in EVs was investigated and various architectures of BEVs and FCEVs were explored. Energy harvesting technologies and their suitability for various topologies and architectures have been analyzed. ESS can affect the harvesting capability and the combinations of various storage units were studied. Regenerative braking harvests significantly more energy than any other harvesting approach and a comprehensive review of its energy harvesting potentials in EVs was conducted. This harvested energy is heavily dependent on the employed strategy. In addition, the effect of driving patterns on the regenerative brake was studied and the difference between BEV and FCEV was highlighted. With the upcoming autonomous vehicles which are mostly electric, the opportunity to recover energy in this new generation of transportation was discussed. Research on the energy recovery from the suspension system was covered. Energy harvesting in the suspension system is more favorable in heavy vehicles and uneven roads and the price and maintenance cost compared to recovered energy are obstacles to their widespread application. Currently, researchers are more interested in the application of solar harvesting in charging stations but with the increase in solar panels' efficiency, its application in FEVs would be more attractive. We also covered methods to harvest energy from tires, wheels, and other experimental approaches. Finally, the gaps in current works and future trends were analyzed. Using look-ahead technologies and long-term road anticipation in BEVs and FCEVs to optimize regenerative braking and fusion of multiple harvesting methods was suggested for future works. This review can provide a guideline for researchers working on vehicles with clean energy.

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