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Onboard Energy Harvesting in Electric Vehicles – Insight and Foresight

Aten M.H. Chau*, Chunhua Liu*†, and Shuangxia Niu**

Abstract – Electric vehicles (EVs) have been identified to be the greenest form of road transportation today. While EVs have the advantage of energy diversification and higher energy efficiency over traditional internal combustion engine vehicles, they are challenged by a limited driving range and high initial cost due to limited energy storage in onboard EV batteries. Therefore, the concept of onboard renewable and reusable energy systems has become increasingly attractive for EVs, serving as a prospective solution to eliminate the woes that once mired the EVs of yesteryear. The purpose of this paper is to give an insight of the latest onboard energy harvesting systems in EVs, and a foresight of future onboard energy harvesting systems for EVs. These include potential benefits and drawbacks, their respective challenges and opportunities, and their prospective integration in future EVs.

Keywords: Energy harvesting, photovoltaic generator, regenerative braking, regenerative shock absorber, thermoelectric generator

1. Introduction

Electric vehicles (EVs) are classified either as pure EVs (PEVs) and hybrid EVs (HEVs) based on their respective propulsion systems, or based on their energy sources, classified as battery EVs (BEVs), HEVs and fuel-cell EVs (FEVs). Electric vehicles with cutting edge energy sources such as ultracapacitors (UCs) and ultraflywheels (UFs), classified as UCEVs and UFEVs are also members of the PEV family) [1].

The HEV family consists of five members, divided into conventional HEVs, refueled using liquid fuel in filling stations, and gridable HEVs (GHEVs), which allow for refueling at filling stations and the ability for charging port recharging. HEVs include micro hybrids, mild hybrids, full hybrids, and GHEVs include plug-in HEVs (PHEVs) and EVs with range extension (REVs) [1][2].

Fig. 1 depicts the overall classification of EVs. Within the PEV family, the BEV is the only variant that is commercially available with practical, non-experimental use. However, from the perspective of the general public, PEVs and BEVs are often muddled by the blanket definition of EVs, which is a vehicle propelled via electrical means. Therefore, BEVs will be used for exemplification purposes in this paper.

Since EVs are challenged by a limited driving range and high initial cost due to limited energy storage in onboard batteries, onboard energy harvesting technologies have become increasingly attractive, serving as a prospective solution to eliminate the woes that once mired the EVs of yesteryear [3]. The purpose of this paper is to give an insight into the latest onboard energy harvesting systems in EVs, and a foresight of future onboard energy harvesting systems for EVs. These include potential benefits and drawbacks, their respective challenges and opportunities, and their prospective integration in future EVs.

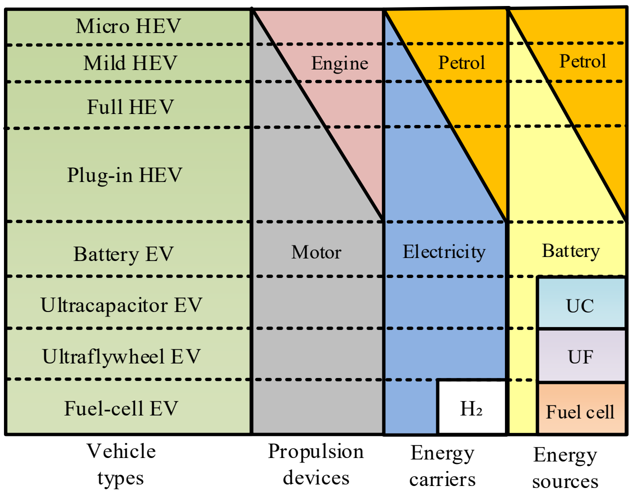


Fig. 1. Classification of various EVs [1]

In recent years, various onboard energy harvesting

*† Corresponding Author: School of Energy and Environment, City University of Hong Kong, Hong Kong, China (chunliu@cityu.edu.hk).
* School of Energy and Environment, City University of Hong Kong, Hong Kong, China (chauaten@ieee.org).
** Dept. of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, Hong Kong, China (shuangxia.niu@polyu.edu.hk).

technologies have been actively developed for EVs. As shown in Fig. 2, there are four viable onboard energy sources that can be harnessed. These include energy from braking, energy from solar light, energy from solar heat, and energy from vibrations.

In terms of harnessing the energy lost during braking, an integral part of modern electric vehicle technology is regenerative braking (RB) [4]. Widely accepted and commercially available in EVs, RB generates electricity when there is a decrease in speed via braking, causing a propulsion motor to work as a generator to produce electricity for onboard battery charging.

To harness energy from solar light, an EV can mount a photovoltaic generator (PVG), colloquially known as a solar panel, on roof surfaces to harness solar light energy to charge onboard batteries – much akin to a contemporary solar vehicle. Current PVG panels incorporate monocrystalline and polycrystalline silicon modules with perovskite-silicon tandem PVG panels being touted as the future once stability issues are resolved, with a potential efficiency of 35 to 40%.

By embedding thermoelectric generator (TEG) devices beneath a solar panel, solar heat can be captured to generate electricity for onboard batteries. A power converter working in tandem with a maximum power point tracking system can also be incorporated to maximise the energy harvested, as both PVGs and TEGs exhibit nonlinear characteristics at while operating in varying irradiance levels and fluctuating temperature conditions.

To harness energy from vibrations, a regenerative shock absorber (RSA), typically an electromagnetic generator can be installed as part of the vehicle's suspension system. Serving as a shock absorber to improve vehicle dynamics on rough surfaces, an EV with four RSAs – one for each wheel, can generate electricity while running on rough road. Recent developments in advanced permanent-magnet linear generator topology such as a vernier permanent-magnet topology or transverse-flux permanent magnet topology, hope to improve efficiency and reduce the size of RSAs in the future.

Recent advances in energy materials have yielded two promising onboard energy harvesting technologies for EVs:

- By integrating TEG into a solar panel, a hybrid PV-TEG system can effectively capture both heat and light solar energy. To accomplish this, integration technologies such as spectral splitters, phase change materials, and thermal systems for performance optimisation are being actively investigated [5].
- A droplet-based electricity generator (DEG) that can convert the kinetic energy from water droplets into electrical energy is being actively developed. Recent developments show that a DEG can generate an open circuit output voltage of 143.5V and a short circuit current of 270.0 µA as a result of continuous rain droplets impinging upon a contact surface 1.6×104 times [6]. This new emerging system opens a new avenue to harness the energy of rainfall for onboard energy harvesting in EVs.

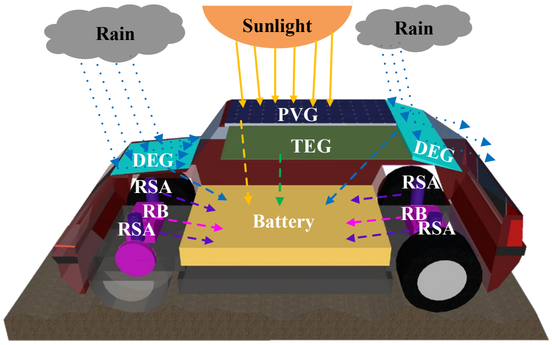


Fig. 2. Onboard energy harvesting technologies in EVs

2. Braking Energy Harvesting

RB recaptures and stores the kinetic energy dissipated by the brake pads during braking using a propulsion motor to function as a generator, extending the driving range by up to 12% [7].

2.1 RB Devices

In an RB device, electric machines play two roles: one as a motor for propulsion and one as a generator for RB, as illustrated in Fig. 3. There are 3 main classes of electric machines used: DC machines, which include the series DC, the shunt DC, the separately excited DC and the permanent magnet (PM) DC[8][9]; AC machines such as cage-rotor induction machines, PM synchronous and PM brushless DC machines; and switched reluctance (SR) machines [10][11][12][13][14].

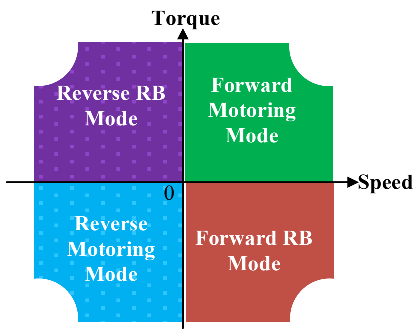


Fig. 3. 4-quadrant operation of electric machines [10]

For DC machines, either a 2-quadrant or 4-quadrant DC chopper is employed to realize RB, with regenerative current returning to the battery through the anti-parallel diodes of the power switches [15].

For AC machines, a 3-phase full-bridge voltage-fed inverter is almost exclusively used for simplicity and the ability for bidirectional power flow. The regenerative currents can then return to the battery through the anti-parallel diodes of the power switches [16].

For SR machines, a SR converter is employed, with the machine windings connected in series with the upper and lower switches to prevent shoot-through faults. RB can be achieved by shifting the phase current to coincide with regions of decreasing phase inductance with rotor position, enabling the regenerative currents to flow back to the battery via two individual diodes [17][18].

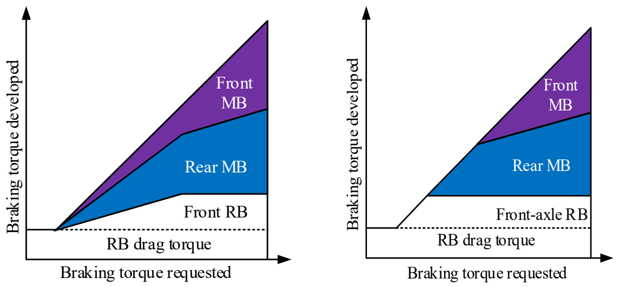
2.2 RB Systems

The following analysis is based on a single machine front-axle configuration due to the prevalence of the same architecture in contemporary, commercially available EVs. The methodology can also be readily extended to single-machine dual axle systems as well as four-machine in-wheel drive architecture.

Due to both machine limitations and safety concerns, joint operation methods incorporating both regenerative and mechanical braking (MB) are used in EVs [19]. There are two major joint operation methods available:

The first joint operation method operates in parallel, as shown in Fig. 4(a). For every input value of torque, the regenerative and mechanical brake work together at a near constant ratio. If the regenerative brake meets the limit for maximum torque, the ratio then delegates work to the mechanical brake. The maximum deliverable torque is dependent on individual drivetrain specifications and the present rotational speed of the electric machine.

The second joint operation method operates in series, as shown in Fig. 4(b). The electric machine delivers the braking torque required, and the mechanical brake is not used unless the braking torque exceeds the current maximum torque value of the machine.



(a) (b)

Fig. 4. RB systems (a) Parallel (b) Series [19]

While the series RB system typically achieves superior energy recovery efficiency, its increased implementation complexity and more stringent safety compliance requirements limit its current adoption. Consequently, parallel RB systems remain the predominant choice in current EVs.

3. Solar Light Energy Harvesting

Photovoltaic technologies are one of the most mature and widely deployed renewable energy solutions, playing a well-established role in reducing carbon emissions and supporting global sustainability efforts [20].

PVGs integrated into EVs enable the direct conversion of solar energy into electrical power for onboard use. Unlike other onboard energy harvesting technologies that rely on motion, PVGs can provide a continuous and externally sourced energy input, making them particularly attractive for improved efficiency and range extension under favourable environmental conditions.

The performance and feasibility of vehicle-integrated PVGs are strongly influenced by material selection, conversion efficiency, and overall system architecture.

3.1 PVG Devices

Electricity generation in a PVG device is based on the photovoltaic effect occurring within a semiconductor p-n junction, as illustrated in Fig.5. Incident photons from sunlight generate electron-hole pairs within the silicon absorber, which are separated by the built-in electric field of the p-n junction. The resulting charge carrier flow is collected by external electrodes, producing a DC output when connected to a load.

Crystalline silicon, specifically monocrystalline silicon, remains the most prevalent and widely adopted material in PVG devices, owing to silicon's abundance in nature. Despite recent advances in more flexible, thin film materials, monocrystalline silicon PV cells still offer comparatively high efficiency, reliability, and considerable maturity in PVG device applications. [21]

Recent developments to improve the efficiency of PVG devices is through the use of Perovskite solar cells (PSCs), shown in Fig. 6. In a PSC, the primary material is perovskite, an inorganic-organic hybrid compound. Due to the material's high optical absorption, carrier mobility, and long diffusion length [22], PVG devices with PSCs offer significant efficiency gains compared to traditional PVG devices, such as those with monocrystalline silicon cells. However, PSCs remain difficult to implement on a wide commercial scale, as PSCs suffer from significant degradation and instability when exposed to adverse environmental conditions, such as moisture and UV radiation. Current PSC developments revolve around optimizing for scalability and research into protective coatings.

Another recent development is the usage of organic solar cells (OSCs) [23]. Unlike conventional PV cells, OSCs operate via excitonic processes. Light absorption in organic semiconductors produces tightly bound electron-hole pairs (excitons), which diffuse to a donor acceptor interface to dissociate into free charges and transported through separate pathways to be collected at electrodes to generate electricity. To enable these excitonic processes, OSCs employ carbon-based semiconductors such as fullerenes (C60) or more recently, non-fullerene acceptors (NFAs) to provide the donor-acceptor interfaces required for efficient exciton dissociation [23]. OSCs offer mechanical flexibility and low weight, making them valuable for prospective vehicle integration. However, they suffer from low power conversion efficiency and low stability, limiting adoption beyond research environments.

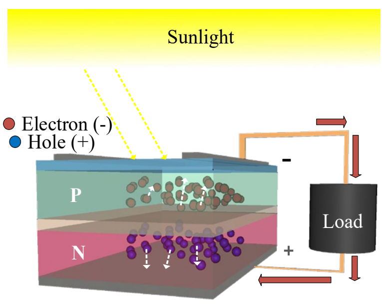


Fig. 5. Schematic diagram of a PV Cell [21]

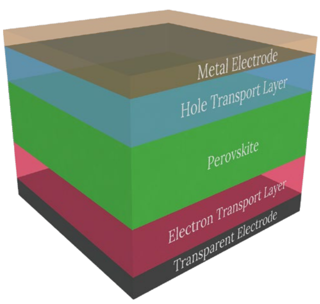


Fig. 6. Perovskite Solar Cell structure [22]

3.2 PVG Systems

PVGs exhibit a nonlinear current-voltage (I-V) characteristic [24] with a maximum power point (MPP) where both products are maximized. In EVs, PVGs operating conditions are non-ideal, where rapidly varying irradiances due to constant motion and wide ambient temperature conditions can cause the MPP to shift frequently. As a result, PVG systems with MPP tracking (MPPT) have been a focus for successful EV-PVG integration.

MPPT regulates the output current and voltage of the PV cell by continuously tracking the peak power point of the PV cells. To optimize the voltage required, a second stage DC-DC converter with other modes of operation can be implemented for when the battery is not delivering power to the motor. For practical implementation, a system, shown in Fig. 7., that separates the charge bus from the recharge bus can be devised, such that the discharge bus can accept charging current from the motor via an integrated RB system. The charge bus can accept charging through three modes of charging, with a constant current mode for when the battery voltage is below the cutoff voltage, the MPPT mode where the PV operates at the maximum power point, and the trickle charge mode, where the battery draws power only to compensate for leakage losses. This method allows PV cells to reliably utilize MPP and maximise the efficiency of onboard battery charging via PVG devices.

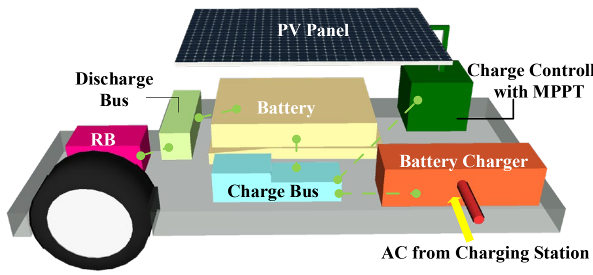


Fig. 7. System for PVG MPPT optimization [1]

4. Solar Heat Energy Harvesting

TEGs offer a solid-state approach to onboard energy harvesting for electric vehicles by directly converting thermal energy into electrical power via the Seebeck effect [25]. By exploiting temperature gradients arising from solar heating on vehicle surfaces, TEGs can provide a supplementary energy source without mechanical components

4.1 TEG Devices

The Seebeck effect dictates that a temperature difference in a conducting material can be converted directly into an electrical voltage. TEGs utilize this effect by using pairs of p-type and n-type semiconductor materials, in which a temperature gradient across the device causes electrons in the n-type material and holes in the p-type material to move from the "hot" side to the "cold side", where their combined motion produces a net voltage. [26-28].

A typical commercial TEG device will have hundreds of TEG couples connected in series. Each TEG couple, shown in Fig 8., contains a hot and cold side, with the n-type and p-type material connected to an electrical conductor and thermal conductor. Current studies show that using bismuth telluride (Bi_2Te_3) as the semiconductor material offers optimal high-energy conversion efficiencies at low temperatures.

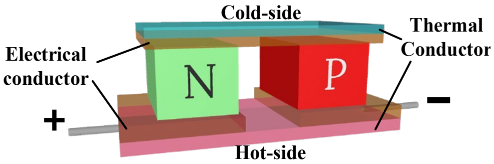


Fig. 8. Configuration of a single TEG Couple [26]

4.2 TEG Systems

TEG systems are typically arranged in a series or parallel connection.

In a series connected TEG system, the system consists of several components: the TEG, a unidirectional DC-DC converter, a controller, a battery, and an electrical load. In this series system, the DC-DC converter processes all TEG output power, while the battery stabilizes DC bus voltages. The controller monitors TEG voltage and current, as well as battery voltage and temperature, and generates PWM signals based on an MPPT algorithm to regulate the converter and ensure safe operation [29][30].

This system can be integrated into the low-voltage battery or DC bus of a multi-voltage energy system, enabling MPPT to be implemented using shared energy management hardware. Charging can then be initiated when the TEG voltage exceeds a minimum threshold, and the battery voltage is below its lower limit and is terminated when the maximum allowable voltage is hit. Three modes of operation are used with this series architecture: battery charging when TEG power exceeds load demand, battery discharging when TEG power is insufficient, and a shutdown of the converter to prevent overvoltage conditions.

In a parallel connected TEG system, shown in Fig. 9., the system instead possesses a bidirectional DC-DC converter. Compared to a series configuration, the parallel configuration enables more flexible power control at the expense of system complexity.

When the TEG output is negligible and the battery state is sufficient, the system operates in a pure battery discharging mode, supplying the load under voltage regulation. Under other operating conditions, MPPT control is activated and the system supports three modes depending on load demand: combined TEG-battery power supply under high load, battery charging under low load, and direct TEG to load power transfer at optimum load condition, extracting maximum power. Without a power conditioning circuit and MPPT, the TEG operating point varies significantly with load resistance. The bidirectional DC-DC converter in this case decouples the TEG from the load, ensuring stable operation at MPP across varying load conditions.

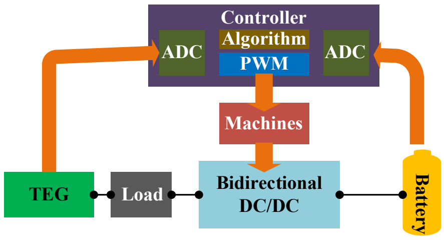


Fig. 9. Parallel connected TEG system [29]

5. Vibration Energy Harvesting

Traditional passive suspension systems, consisting of a spring and viscous damper, are limited by a fixed, non-adjustable damping force. Active suspension systems overcome this limitation by employing actuators to provide variable damping and near-ideal vibration isolation; however, this improved performance comes at the cost of increased energy consumption during parts of the operating cycle [31].

Integrating energy-harvesting functionality into active suspension offers a promising solution, enabling suspension vibrations induced by road irregularities to be converted into electrical energy and stored in onboard batteries. Theoretical studies indicate that RSAs can improve vehicle fuel efficiency by up to 10% [32].

A regenerative suspension system can be classified as mechanically or electromagnetically regenerative. In this paper, only electromagnetically regenerative suspension systems and devices will be highlighted.

5.1 RSA Devices

A PM machine is typically used for electromagnetic suspension systems (EMS). While operating in actuator mode, PM machines can provide an active force, and while in generator mode, a damping force through the tuning of shunt resistances. There are several types of RSA devices for utilizing PM machines for usage in EMS devices:

The first type converts linear motion upon compression into rotation. This can be realized by either utilizing a ball-screw system shown in Fig.10(a)., where the advancement of a screw into a nut rotates a motor [33], or a rack and pinion system, incorporating a bevel gear to change the directional axis to be in parallel , via the “rack”, with linear motion [34].

Another type is a hydraulic electromagnetic shock absorber (HESA) [35] shown in Fig. 10(b)., capable of both vibration isolation and energy recuperation. Reciprocating piston motion drives high-pressure oil through a Wheatstone bridge type hydraulic rectifier and accumulators, which regulate flow before powering a hydraulic motor and generator.

A recent development is an RSA integrated with a linear generator [36][37], shown in Fig. 11. The device converts relative vibration between the wheel and sprung mass into electricity via linear electromagnetic induction. The RSA is comprised of an integrated PM assembly and a concentric coil assembly, with ring shaped magnets and high-permeability materials arranged to direct magnetic flux radially and enhance flux density within the coils. As the coils move through the magnetic field, an induced voltage is generated and subsequently rectified for energy recovery.

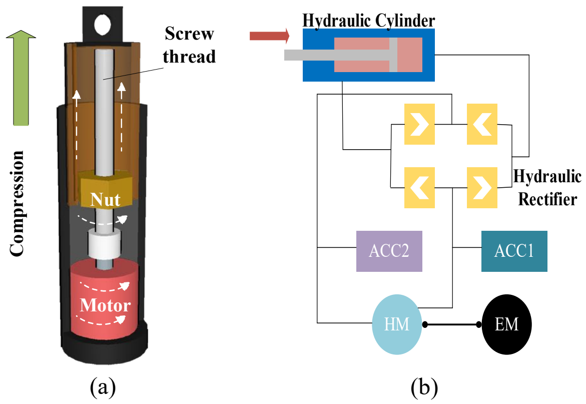


Fig. 10. Regenerative shock absorber devices. (a) Ball-Screw damper. [33] (b) HESA System. [35]

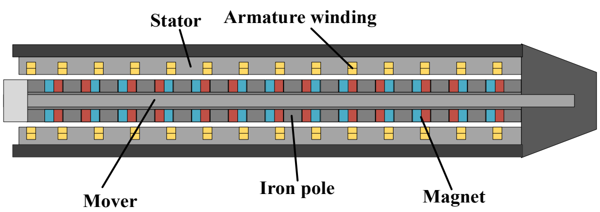


Fig. 11. Linear-machine based energy harvester [37]

5.2 RSA Systems

RSA systems operate on a dual-loop control system based on state feedback [38], shown in Fig 12. The system contains one outer low-bandwidth inertial rate loop and one inner high-bandwidth current loop, in which there are three major components – a vehicle dynamics controller, a power electronic converter, and DC/DC power stages.

The vehicle dynamics controller processes inertial and relative motion feedback within a skyhook-based framework to regulate sprung-mass dynamics. Using the vertical inertial velocity of the sprung mass and relative suspension velocities at each wheel, it generates the desired actuator force commands for all four wheels, emulating various suspension behaviour through electrical actuation.

Next, the power electronic controller receives the actuator force commands together with the operating mode and electrical feedback signals from the DC/DC power stage. Measured voltages and currents are used to form force error signals, from which control inputs to the power stage are generated. This controller also governs the switched-bridge topology, determining the direction of energy flow (traction or regeneration) and enforcing appropriate voltage rectification.

The DC/DC power stage implements the control inputs while accounting for the surrounding bridge topology. Based on a gyrator model [39], it provides a controlled electrical coupling between the battery and linear generators, enabling simultaneous force control and energy regeneration through regulated power flow and current control.

The linear generators allow for physical processes, responding to control forces and road-induced disturbances provided by suspension mounted relative motion sensors and inertial accelerometers on the sprung mass.

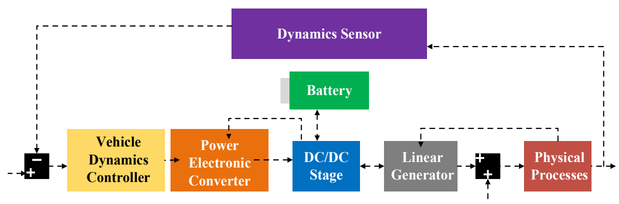


Fig. 12. Control block diagram of an active RSA system [38]

6. The Next Frontier in Energy Harvesting

6.1 Hybrid PV-TEG Systems

Despite the broad spectrum of solar irradiance, PVGs are only able to convert a fraction of the incident energy into electrical power, with the remainder dissipated as heat. The resulting temperature rise degrades both the efficiency and the operational lifetime of PVGs. To address this limitation, TEGs can be integrated with PVGs to recover a portion of the thermal energy. The first hybrid PVG-TEG system was proposed in 1979, known as the thermophotovoltaic solar energy conversion system [40]. Owing to its high system complexity and cost, its early development was limited. Recent advances in materials and integration techniques over the past decade in hybrid PVG-TEG systems, enabling their promising application in EVs [41], [42]

By integrating both PVG and TEG devices, the hybrid PVG-TEG system can effectively convert around 349-949 nm of the solar spectrum with the PVG device and around 949-2500 nm with the TEG device [43]. There are two main approaches for device integration: the first is to split the solar spectrum to direct shorter wavelength photons to the PVG and longer wavelength photons to the TEG [44]. The second involves directly connecting the TEG and PVG thermally [45], which is more compact and less complex, making it well suited for potential EV applications.

In the field of PVGs, concentrated PVG systems employ optical elements such as Fresnel lenses to focus sunlight into small-area, high-efficiency PV cells. This approach reduces the required active area, improves cost effectiveness, and enhances overall conversion efficiency. As shown in Fig. 13, a hybrid concentrated PVG-TEG system integrates a TEG directly beneath the PVG to recover thermal energy, with a heat sink attached to the cold side of the TEG to maintain a temperature gradient [46]. Experimental performance characteristics indicate that the total system efficiency can be significantly improved, particularly under higher solar concentration levels [47].

To enhance heat transfer from the PVG to the TEG, a flat-plate micro-channel heat pipe (MCHP) has been proposed. As illustrated in Fig.14, the MCHP evaporator is positioned beneath the PVG, while the condenser is mounted on top of the TEG [48]. This configuration enables efficient energy transfer of thermal energy from the PVG to the TEG via fluid circulation, thereby increasing the temperature gradient across the TEG relative to the heat sink and enhancing electrical power generation. Experimental results indicate that this hybrid system achieves 14.0% higher electrical efficiency compared with a standalone PVG.

As an alternative to heat pipes, phase change materials (PCMs) have been proposed as effective thermal management agents for PVGs [49]. As illustrated in Fig. 15, PCMs absorb heat generated by the PVG with minimal temperature rise, thereby maintaining a stable temperature gradient for thermoelectric power generation [50]. Alternatively, PCMs can be integrated with the cold plate of the TEG to further increase the temperature gradient across the TEG, resulting in improved electrical output and overall system efficiency compared with standalone PVGs or conventional PVG-TEG hybrid configurations [51]

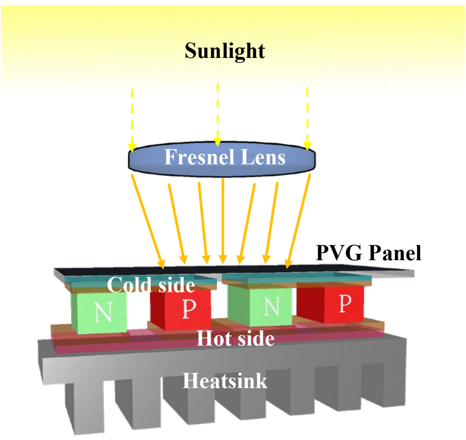


Fig. 13. Hybrid PV-TEG system [46]

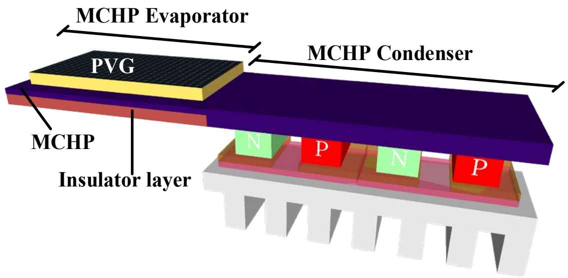


Fig. 14. Hybrid PVG-TEG-MCHP system [48]

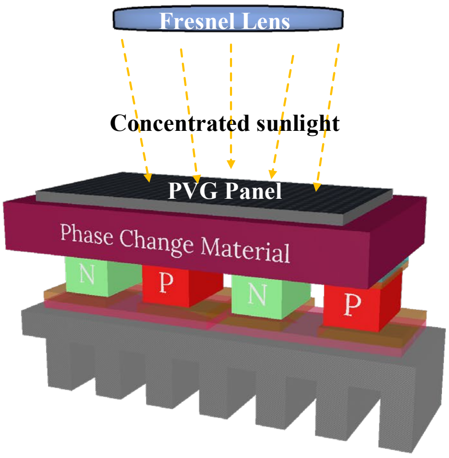


Fig. 15. Hybrid PV-TEG-PCM system [49]

6.2 DEG Systems

Despite their abundance, the kinetic energy contained in raindrops has remained largely underexploited, primarily due to the low frequency and irregular nature of these motions, which are poorly suited for conventional electromagnetic energy harvesting systems. Advancements in energy materials have allowed a range of alternative harvesting technologies to emerge over the past decade, including triboelectric nanogenerators (TENGs), hydrovoltaic and reverse electrodialysis systems, and piezoelectric nanogerators (PENGs). These advanced technologies aim to harvest the untapped kinetic energy sources in raindrops and other water sources for practical electronics systems. [52-54]

Among these approaches, TENGs were amongst the earliest to demonstrate effective low-frequency energy harvesting. TENGs exploit a contact electrification method known as triboelectrification, a method in which electrostatic charges are generated through the contact and separation of materials with differing electron affinities. By periodically bringing oppositely charged surfaces into contact and separating them, charge transfer is induced, driving electron flow through an external circuit and generating electrical power.

A TENG with a superhydrophobic micro-nanostructured polytetrafluoroethylene (PTFE) surface has been developed to harvest water-related energy. A 30-µL water drop can achieve a peak voltage of 9.3 V and a peak current of 17 µA, thus creating a maximum output power of 145 µW when paired with a 5 MΩ load resistor. Under a flowing tap, the output current and instantaneous power densities reach 1.5 $\mu A/cm^2$ and 20 mW/cm^2 respectively, allowing for the ability to directly drive 20 LEDs [55].

Owing to interfacial limitations of dielectric materials and their interactions with liquids, TENGs suffer from a restricted power density. To overcome this constraint, a DEG has been proposed and developed to harvest energy from impinging water droplets, shown in Fig. 16. In this approach, the spreading of a droplet upon impact bridges initially disconnected electrodes, forming a closed electrical circuit and converting an interfacial charge transfer process into a bulk effect, thereby substantially enhancing the power density. The DEG consists of a PTFE film deposited on an indium tin oxide (ITO) substrate with an aluminium electrode, achieving an open-circuit voltage of 143.5V and a short-circuit current of 270.0 µA at a droplet frequency of 4.2 Hz. Under a load resistance of 332 kΩ, an instantaneous peak power density of 50.1 W m^{-2} is obtained, allowing a single 100 µL droplet released from a height of 15 cm device to light up 100 LEDs.

The DEG device under experimental conditions also demonstrates greater robustness compared to conventional water-based triboelectric systems. Under high humidity conditions, the device can maintain output while recovering surface charge once humidity is reduced, whereas previous triboelectric systems often suffer from degraded performance under similar conditions.

In addition to the device's optically transparent nature, the demonstrated practical outdoor performance allows this new emerging system to open a new avenue for onboard energy harvesting technologies in EVs.

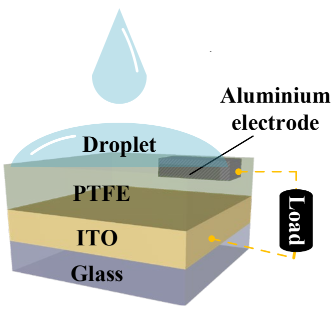


Fig. 16. DEG structure with PTFE film [6]

7. Insight and Foresight

Growing environmental concerns, global decarbonization targets, and various national government incentives promoting EV adoption are accelerating investment in EV technologies and supporting infrastructure, creating a bright future for advancements in onboard energy harvesting systems. While RB and PVG systems have seen mature adoption in contemporary EVs, developments in multifunctional vehicle surfaces, incorporating DEGs or PVG-TEG hybrid systems appear to be increasingly promising. DEGs are particularly compelling, as the constant motion of a vehicle through rain allows DEG modules to reduce pooling effects that limit their efficiency during static operation. Future developments in similar intelligent body panels, smart materials, or energy-harvesting skins will allow for significant advancements in onboard energy harvesting systems.

The primary challenge for EVs lies not only in individual devices or machine efficiency, but in further system integration, transportation infrastructure development, and supportive policy frameworks allowing for easier adoption of cutting-edge technologies for future EVs. Charging station availability, grid capacity and stability, as well as renewable energy penetration ultimately shape the broader sustainability impact of EVs. Investment and incentives in developing similar, small scale onboard regenerative technologies may see applications beyond contemporary road transportation, allowing these technologies to trickle down towards widespread adoption in a multitude of renewable energy systems. Although far from primary energy sources, onboard harvesting technologies are well suited as distributed micro-generation enhancements that incrementally reduce grid dependence and increase overall system resilience, favourable attributes that once again extend beyond mere contemporary road transportation.

5. Conclusion

This paper has reviewed a range of onboard energy harvesting technologies and systems for EVs, highlighting their complementary roles in improving energy utilization. While individual harvesting mechanisms offer limited contributions, their integration within system architectures with a multitude of energy sources presents a promising pathway for improving vehicle efficiency and sustainability. Advances in materials, machine topologies, and power electronic control strategies further enhance system efficiency.

As EV technologies continue to evolve with increasing alacrity, underpinned by supportive, effective infrastructure and incentives, the strategic integration of onboard energy harvesting technologies will compound the inherent benefits of broader electrified transportation systems.

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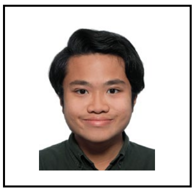
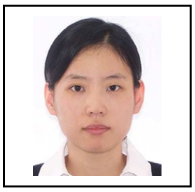


Aten Man Ho Chau received his B.Sc. degree in electronics and electrical engineering from The University of Edinburgh. He is currently a Research Assistant at The City University of Hong Kong. His research interests include Electric and Hybrid Vehicle Technologies, Renewable Energy Systems, and Sustainability Policy.

Chunhua Liu (Senior Member, IEEE) received his B.Eng. and M.Eng. degrees in automatic control from the Beijing Institute of Technology, and his Ph.D. degree in electrical and electronic engineering from The University of Hong Kong. He is currently the Chair Professor of electrical and electronic engineering with the School of Energy and Environment at the City University of Hong Kong. He has authored and coauthored more than 250 papers in leading journals covering a wide range of research interests including Electric Vehicle Technologies, Renewable Energy Systems, Smart Devices for Robotics, as well as Smart Grid and Microgrid Technologies.



Shuangxia Niu (Senior Member, IEEE) received her B.Sc. and M.Sc. degrees in electrical engineering from Tianjin University and her Ph.D. degree in electrical and electronic engineering from The University of Hong Kong. She is currently a Professor with the Department of Electrical and Electronic Engineering at The Hong Kong Polytechnic University. She has authored and coauthored more than 250 papers in leading journals. Her research interests include Electric Vehicle Technologies, Renewable Energy Systems, Machines and Drives, Power Electronics Technologies, as well as Applied Electromagnetics, Numerical Methods and Optimisation.