Developing Mechanisms to Capture Waste Energy from EV Motors And Convert It into Usable Electrical Energy

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Abstract- Electric vehicles (EVs) use high-efficiency motors (≈90% efficient) and regenerative braking to recapture kinetic energy, yet a nontrivial fraction of input power is still lost as waste heat. This paper investigates mechanisms to harvest waste heat from EV motors and recover it as electricity, supplementing existing regenerative braking systems. We review literature on thermoelectric generators (TEGs) and other recovery methods in automotive applications, then describe a simulation of an EV driving cycle with regenerative braking and an integrated TEG on the motor. The simulation quantifies energy flows: battery energy used, kinetic energy recovered, and heat losses. Results indicate that, in typical city-stop driving, regenerative braking can recover on the order of 50–60% of braking energy, whereas motor waste heat is much smaller (on the order of 10% of power input). A practical TEG on the motor (assumed 5% conversion efficiency) would only recover a few watts (≈0.3% of brake heat), yielding negligible battery energy compared to regen. However, even a few watts could power sensors or auxiliaries. We discuss simulation results, illustrate energy balances in tables, and suggest that waste-heat recovery in EVs remains challenging but offers marginal gains in efficiency.

Indexed Terms- Electric Vehicle (EV), Waste Heat Recovery, Thermoelectric Generator (TEG), Regenerative Braking, Energy Simulation.

I. INTRODUCTION

Electric vehicles have much higher drive-train efficiency than internal-combustion vehicles, but they still produce waste heat. Modern EV traction motors convert about 90% of electrical input to mechanical work, implying roughly 10% of the power is lost as heat in the motor and inverter. In addition, conventional friction brakes on EVs generate heat when regenerative braking cannot recover all kinetic energy. Regenerative braking recovers kinetic energy during deceleration by running the motor as a generator, improving urban driving efficiency significantly. For example, experiments show that typical regenerative systems can achieve on the order of 50–60% efficiency [2][2][3]. Nevertheless, in real driving some kinetic energy is still dissipated as heat (especially at low speeds where regen is disabled) and the motor itself generates heat whenever it operates.

Despite the success of regenerative braking in recapturing kinetic energy, [4] stated that, a nontrivial fraction of both propulsion input and braking energy remains unrecovered and is lost as heat. In typical stop-go driving, EV motors dump roughly 10 % of their electrical input as thermal losses, and conventional brakes dissipate approximately 40 % of kinetic energy in the form of heat. Presently, these losses reduce overall vehicle efficiency and place additional load on thermal-management systems. While TEGs offer a potential path to convert some of this waste heat into electricity, real-world trials indicate conversion efficiencies on the order of 0.3 %–1 %, yielding only a few watts of recovered power [5][6]. A systematic, simulation-based analysis is needed to quantify the true benefit of integrating TEGs alongside regenerative braking in EVs.

To this end, we simulate a prototypical urban driving cycle comprising five accelerate–cruise–stop sequences for a 1,500 kg EV with a 50-kW motor. Key parameters include a motor/inverter efficiency of

90 %, regenerative braking efficiency of 60 %, and a motor-mounted TEG with 5 % conversion efficiency. We quantified energy flows, battery input, kinetic energy recovered, motor heat losses, brake heat losses, and compare net battery usage with and without TEG integration. By isolating propulsion and thermal recovery effects (neglecting aerodynamic drag, rolling resistance, and battery inefficiencies), the study rigorously assesses the marginal gains afforded by waste-heat harvesting. This study focuses on thermal waste energy from EV motors and how to convert it to electricity. As one approach, thermoelectric generators (TEGs) can be attached to motor casings or exhausts to convert temperature differences into electric power via the Seebeck effect.

II. EMPIRICAL REVIEW

A. EV Motor Efficiency and Waste Heat

EV motors are much more efficient than combustion engines; manufacturers estimate motor efficiencies by around 90% or higher. As [7][8] note, a typical EV motor wastes only ~10% of electrical energy as heat. (This excludes other losses in battery/inverter systems.) Nonetheless, even 10% can represent several kilowatts under high load. Studies of EV thermal management show that motor winding and core losses generate heat that must be dissipated by cooling systems; some researchers have explored using that heat. For instance, [9] proposed a motor waste-heat power generation system using TEGs, converting the motor's hot surface temperature into electrical energy to charge the battery. Such designs demonstrate feasibility, but practical output is limited by motor surface temperature and TEG efficiency.

B. Regenerative braking

Regenerative braking is a widely used technology to recover kinetic energy when slowing an EV. The motor operates as a generator, feeding energy back to the battery. Literature reports vary, but [10] found that a BMW i3 EV's regen system could recover up to about 60.1% of the available kinetic energy during an urban stop-and-go route. (In contrast, pure potential-energy recovery via coasting downhills could yield ~88% under ideal conditions.) Other sources indicate that regenerative braking can reduce energy consumption by on the order of 20–30% in typical city driving. Regenerative efficiency depends on vehicle speed and battery state – most systems cut off regen below a few km/h, so very low-speed kinetic energy is still lost to friction brakes.

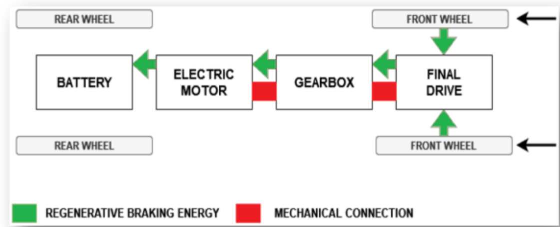

Figure 1: Regenerative braking system layout

[2] note that the energy recovery system in electric vehicles includes a generator that converts kinetic energy into electrical energy, an energy storage device like an electrochemical battery, a controller managing the process, sensors monitoring system parameters, and software controlling the controller's operation based on sensor data.

C. Waste-heat recovery methods

Outside EV-specific motors, much work focuses on capturing exhaust heat from combustion engines using TEGs. In EVs, the analogous waste heat streams are motor/inverter heat and brake-disc heat. Brake-disc TEGs: One study by [11] applied finite-element thermal analysis to a brake disc and pad assembly and simulated attaching TEGs to the disc surfaces. They found that only about 0.3% of the frictional heating is converted into electricity, corresponding to roughly 4 W of continuous power under typical braking. While this is a tiny fraction of brake energy, it could nonetheless power vehicle instrumentation or improve net efficiency slightly. Motor/inverter TEGs: Several investigations propose mounting TEG modules on the electric motor housing or power electronics to utilize their waste heat. For example, [9] described a TEG-equipped EV motor system and reported experimental results (details not given in the abstract). In general, EV motor TEG systems face challenges: electric motors run relatively cool (often <100 °C), so temperature gradients are modest. Advanced thermoelectric materials can improve conversion, but real-world efficiencies are still low (on the order of 1% at best).

III. MATERIALS AND METHODS

We considered a simplified EV with the following representative parameters: mass 1,500 kg, motor peak power 50 kW, motor/inverter efficiency ~90% during acceleration and motoring, and regenerative braking capability up to 60% of braking energy (reflecting typical hardware limits). The battery is assumed to be large enough to accept all returned energy, with negligible cycling losses for this analysis. The motor generates heat equal to (1–efficiency) of electrical input. For simplicity, we assume the motor dissipates ~10% of input power as thermal losses (consistent with 90% efficiency).

We simulate an urban-style driving cycle with repeated stops. A prototypical cycle consists of five accelerate–cruise–stop events: from rest, accelerate at 3 m/s² to 80 km/h (22.2 m/s), cruise briefly, then brake to zero, remain stopped for 5 s, and repeat. This pattern yields frequent braking and opportunities for regen. The cycle duration is on the order of 100 seconds; total distance is on the order of a few hundred meters per cycle. While not a standardized drive cycle, it captures stop-and-go dynamics typical of city driving.

Table 1: Vehicle and System Parameters

Parameter	Symbol	Value	Unit	Remarks
Vehicle mass	m	1,500	Kg	Typical compact electric vehicle
Target speed per cycle	v	22.2	m/s (80 km/h)	Max speed per stop–go event
Motor/inverter efficiency	η_m	0.90	—	90% efficient
Regen brake energy recovery ratio	η_r	0.60	—	60% of kinetic energy recovered
TEG conversion efficiency	η_{TEG}	0.05	—	Optimistic thermoelectric conversion
Number of stop–go cycles	N	5	—	Simulates urban stop-and-go scenario

Step 1: The fundamental starting point is to calculate the kinetic energy gained by the vehicle during acceleration. This energy depends on the mass m of the EV and the target velocity v reached during acceleration, so determining the kinetic energy gained by the vehicle during acceleration will enable us to understand the behavior of the vehicle. This kinetic energy is what needs to be supplied by the vehicle and, conversely, what becomes available for recovery during regenerative braking or thermal conversion when the vehicle slows down.

$$\Delta KE = \frac{1}{2} mv^2 \quad (1)$$

where m and v are the mass and speed of the vehicle respectively.

Step 2: After calculating the kinetic energy gained by the vehicle during acceleration, the next step considered was calculating the motor input energy per acceleration. This determines the total electrical energy drawn from the battery to generate the kinetic energy.

Since motors are not perfectly efficient, this equation adjusts for the motor efficiency η_m.

It links mechanical performance with electrical consumption, a key step in analyzing EV energy use.

$$E_{motor\_in} = \frac{\Delta KE}{\eta_m} \quad (2)$$

Step 3: The total energy put was estimated with equation. Here, N is the number of cycles (either acceleration or deceleration).

$$E_{battery\_total} = N \times E_{motor\_in} \quad (3)$$

Step 4: We further quantified the amount of electrical energy that was lost as heat during motor operation, representing energy that does not contribute to motion but is instead dissipated thermally. Since no electric motor is perfectly efficient, a portion of the input energy was inevitably converted to waste heat, and this equation isolates that quantity.

This heat presents a valuable opportunity for secondary energy harvesting via thermoelectric generators (TEGs), making this equation central to waste heat recovery modeling.

$$Q_{motor\ heat} = (1 - \eta_m) \times E_{battery\_total} \quad 4$$

Step 5: During the recovery process, not all the total energy was recaptured. So, we calculated the fraction of kinetic energy that was not recovered during braking and was instead lost as heat through friction at the brake pads. Although regenerative braking can reclaim a portion of the kinetic energy, mechanical brakes are still required for complete stops or rapid deceleration, especially at low speeds or in emergencies.

$$Q_{brake}=(1-\eta\_r) \times \Delta KE \times N \quad 5$$

where η_r is the regenerative efficiency.

Step 6: The regenerated energy needs to be returned to the battery, so modeled a mathematical equation to calculate the amount of kinetic energy that can be recaptured by the regenerative braking system during deceleration.

The regeneration efficiency η_r reflects the effectiveness of the braking system in converting mechanical energy back into electrical energy that can recharge the battery.

This recovered energy offsets part of the energy originally supplied by the battery, thereby increasing the vehicle's overall energy efficiency and extending driving range.

$$E_{\_regen}= \eta\_r \times \Delta KE \times N \quad 6$$

Step 7: We further calculated the net energy consumed from the battery, excluding the energy recovered during regenerative braking, as it reflects the effective cost of propulsion after energy savings through regen. This value is essential for understanding how much the battery must truly deliver to support driving.

$$E_{net} = E_{battery\_total} - E_{regen} \quad 7$$

Step 8: Equation 8 was modelled to estimate the electrical energy output of a TEG system attached to the motor. The TEG converts a fraction of the motor's waste heat into usable electricity, governed by its efficiency η_TEG. This is the core equation linking thermal waste recovery to battery energy replenishment.

$$E_{TEG} = \eta_{TEG} \times Q_{motor\ heat} \quad 8$$

Step 9: Finaly, equation 9 was modelled to estimate the net battery energy after accounting for both regen and TEG recovery. It indicates the actual battery draw when both kinetic and thermal recovery mechanisms are active. This helps quantify the impact of TEG systems on vehicle energy usage.

$$E_{net\_TEG} = E_{net} - E_{TEG} \quad 9$$

The simulation (implemented in MATLAB/Python) computes: (a) total battery energy used for the driving cycle, (b) kinetic energy recovered via regen, (c) motor waste heat, (d) brake heat, and (e) electrical energy recovered by the TEG. These results are tabulated to compare scenarios with and without waste-heat recovery.

IV. RESULTS AND DISCUSSION

Figure 2 shows the simulated energy distribution for an urban driving scenario consisting of five accelerate–decelerate cycles. The battery electrical input is the largest energy component at 2,053.5 kJ, reflecting the total electrical energy drawn from the battery to accelerate the 1,500 kg vehicle to 22.2 m/s (≈80 km/h) and maintain its motion. This value integrates the motor's 90 % efficiency, indicating that the actual mechanical energy requirement (~1,848 kJ per cycle) is augmented by 10 % to account for conversion losses. The high magnitude of this bar underscores the dominant role of propulsion energy demand in an EV's overall energy budget during stop-and-go urban driving.

The regenerative braking recovery bar shows 1,108.8 kJ returned to the battery, equivalent to 60 % of the theoretical kinetic energy available during each deceleration phase. This considerable recovery rate highlights the effectiveness of regenerative braking in recapturing motion energy that would otherwise be dissipated as heat. However, despite this recuperation, the chart shows a substantial residual brake heat loss of 739.2 kJ (40 %), evidencing the limits of current regen systems, particularly at lower speeds where mechanical brakes must supplement electrical regen. These two bars taken together illustrate that roughly half of the input energy is recovered mechanically, but a significant fraction still ends up as brake heat.

In comparison, motor waste heat which is the thermal energy dissipated from motor and inverter inefficiencies, amounts to 205.4 kJ, or 10 % of the battery input. This loss channel is considerably smaller than both the battery input and the unrecouped brake energy but remains a nontrivial source of low-grade thermal energy. The TEG output bar, showing 10.3 kJ, represents the 5 % conversion of this motor waste heat into electricity via thermoelectric generators. Although modest, this gain demonstrates that even a small fraction of thermal losses can be reclaimed to supply auxiliary loads or slightly offset the battery draw.

Finally, the net battery used after accounting for both regenerative braking and TEG recovery stands at 934.4 kJ, illustrating that the combined recovery strategies reduce the raw battery demand from 2,053.5 kJ by more than half. In practical terms, regenerative braking recovers roughly 54 % of the propulsion energy, and TEG recovery contributes an additional ~1 % improvement, delivering a marginal but measurable benefit. These results underscore that while regenerative braking remains the primary mechanism for energy recuperation in EVs, integrating waste-heat recovery systems can incrementally enhance overall efficiency, particularly valuable for powering auxiliary systems or extending range in cold climates where waste heat might otherwise be discarded.

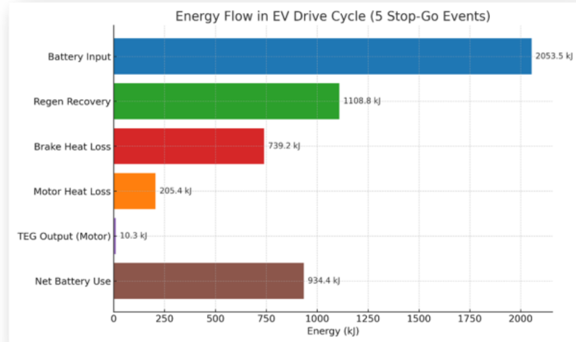

Figure 2: Energy Flow Distribution in EV Drive Cycle Over Five Stop–Go Events

CONCLUSION

This paper explores innovative strategies for harnessing waste heat generated by electric vehicle (EV) motors and converting it into usable electrical energy, with the goal of supplementing the energy recovered through conventional regenerative braking systems. Through a comprehensive review of existing literature, it becomes clear that inefficiencies in EV motors typically accounting for approximately 10% of the input electrical energy alongside heat produced by friction braking, constitute the primary sources of thermal energy loss in electric drivetrains. Among the technologies proposed to reclaim this wasted energy, thermoelectric generator (TEG) systems have garnered significant attention due to their ability to directly convert temperature gradients into electrical power without moving parts.

To assess the practical viability of this concept, we conducted a simulation of a representative EV drive cycle incorporating regenerative braking. The results indicate that regenerative braking alone can recover approximately 50% of the kinetic energy typically lost during deceleration. In contrast, the amount of energy dissipated as heat from motor inefficiencies is comparatively smaller. Even under optimistic assumptions regarding TEG performance such as a conversion efficiency of 5%, the amount of electrical energy recoverable from motor heat remains limited. Specifically, our simulation showed that such a TEG configuration could recover roughly 10 kilojoules (kJ) of energy over a 100-second driving interval. While this amount is negligible compared to the hundreds of kilojoules regained via regenerative braking, it is nonetheless potentially sufficient to support low-power vehicle systems, such as sensors, microcontrollers, or dashboard electronics.

These simulation findings are consistent with published empirical studies, which report that current thermoelectric recovery systems in automotive applications typically generate electrical power in the single-digit watt range. This underscores a fundamental limitation of present-day thermoelectric materials and system designs when it comes to large-scale energy recovery from EV motor waste heat. As a result, regenerative braking continues to dominate as the most effective method for recapturing energy in electric vehicles.

Nonetheless, ongoing advances in thermoelectric materials aimed at increasing their efficiency, reducing cost, and improving integration could eventually enhance the viability of waste heat recovery systems. In the future, such improvements may enable EVs to recover a greater fraction of the thermal energy currently lost, thereby modestly extending vehicle range or reducing dependency on the main battery for auxiliary loads. By providing a simulation-based quantitative analysis, this study contributes to a clearer understanding of the potential and current limitations of converting EV motor waste heat into electricity, helping to frame realistic expectations for its role in future vehicle energy management strategies.

REFERENCES

[1] Sandrini, G., Chindamo, D. and Gadola, M., 2022. Regenerative braking logic that maximizes energy recovery ensuring the vehicle stability. Energies, 15(16), p.5846.

[2] Szumska, E.M., 2025. Regenerative Braking Systems in Electric Vehicles: A Comprehensive Review of Design, Control Strategies, and Efficiency Challenges. Energies, 18(10), p.2422.

[3] Hamada, A.T. and Orhan, M.F., 2022. An overview of regenerative braking systems. Journal of Energy Storage, 52, p.105033.

[4] Georgiev, P., De Filippis, G., Gruber, P. and Sorniotti, A., 2023. On the benefits of active aerodynamics on energy recuperation in hybrid and fully electric vehicles. Energies, 16(15), p.5843.

[5] Araiz, M., Casi, Á., Catalán, L., Martínez, Á. and Astrain, D., 2020. Prospects of waste-heat recovery from a real industry using thermoelectric generators: Economic and power output analysis. Energy Conversion and Management, 205, p.112376.

[6] Andrews, J., Andrews, J.G., Jelley, N.A. and Jelley, N., 2022. Energy science: principles, technologies, and impacts. Oxford university press.

[7] Shen, K., 2024. Energy Efficiency and Life Cycle Analysis of Sustainable Battery-powered Electric Vehicle Technologies (Doctoral dissertation, Case Western Reserve University).

[8] Renault Group, 2021. The energy efficiency of an electric car motor. Renault Magazine, 9 March. [online]Availableat: https://www.renaultgroup.com/en/magazine/energy-and-motorization/the-energy-efficiency-of-an-electric-car-motor/ [Accessed 9 Jun. 2025].

[9] Siyang, L., Lam, K.H. and Cheng, K.W.E., 2016. Development of a motor waste heat power generation system based on thermoelectric generators. In: 2016 International Symposium on Electrical Engineering (ISEE). Hong Kong, Dec. 2016. IEEE. https://doi.org/10.1109/ISEE.2016.7845984.

[10] Armenta-Déu, C. and Cortés, H., 2023. Analysis of kinetic energy recovery systems in electric vehicles. Vehicles, 5(2), pp.387–403. https://doi.org/10.3390/vehicles5020022.

[11] Coulibaly, A., Zioui, N., Bentouba, S., Kelouwani, S. and Bourouis, M., 2021. Use of thermoelectric generators to harvest energy from motor vehicle brake discs. Case Studies in Thermal Engineering, 28, p.101379. https://doi.org/10.1016/j.csite.2021.101379.