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A Review of the Overall Efficiency of Automotive Energy Recovery Systems in Extending Travel Range

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Abstract. Due to the environmental concerns associated with conventional fuel vehicles, improving overall vehicle efficiency has become a key research priority. This paper investigates whether automotive energy recovery systems can effectively enhance efficiency and extend travel distance using the same input energy. Multiple recovery methods—including regenerative braking, mechanical flywheels, thermoelectric generators, Rankine cycle systems, and electric turbochargers—are assessed based on their overall efficiency. These systems aim to recollect and utilize waste energy to improve performance. Among hybrid vehicles, energy recovery remains the most critical factor for efficiency gains. Test results indicate that each method offers measurable benefits, such as reduced battery stress, improved acceleration, and extended range. Mechanical flywheels emerged as the most feasible solution, closely followed by regenerative braking. While all systems show potential, future studies must focus on optimizing control strategies and validating effectiveness under real-world, transient conditions to ensure consistent and scalable improvements in automotive efficiency.

Keywords: Energy Recovery Systems, Overall Efficiency, Hybrid Vehicle Optimization, Waste Heat Utilization

1. Introduction

Using sustainable transportation helps reduce carbon emissions, alleviate traffic congestion, and promote a healthier, more environmentally friendly lifestyle. In sustainable mobility, hybrid vehicles are pivotal but limited by unrecaptured energy losses. Unlocking their full potential demands synergizing key technologies: Regenerative braking recovers kinetic energy during deceleration, amplified by mechanical flywheels that store excess energy efficiently for rapid reuse. Waste heat from engines and exhaust long squandered is harnessed via thermoelectric generators and Rankine cycles. Meanwhile, electric turbochargers eliminate lag, optimizing engine performance across

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speeds to cut inefficient combustion. Integrating these things such as Kinetic Energy Recovery systems (KERS), waste heat reuse, and engine optimization drives unprecedented energy utilization, slashing fuel use and emissions, and accelerating progress toward carbon neutrality. Therefore, we will conduct research on how to significantly enhance overall efficiency.

Pole-changing induction machine PCIMs have been studied for their advantages in torque density, fault tolerance, and wide speed ranges, with research focusing on modeling and winding design [1,2]. Karatzaferi, et al. [3] addresses this by proposing methods to calculate energy during braking and determine optimal braking periods, laying groundwork for maximizing the amount of energy recaptured during braking events. Heydari, et al. [4] develops a low-speed cutoff detection mechanism to identify when regenerative braking becomes ineffective, highlighting the need for solutions to extend efficient braking to lower speed ranges.

Flywheel KERS is investigated here as a mechanical buffer that circumvents the round-trip losses and power-rate limits inherent to electrochemical storage. Earlier foundational work established the principle: Sun et al. [5] employing a 300 m s^{-1} rim-speed, 0.7 radius-ratio planetary gear set and Ershad et al. [6] using a 20 kr min^{-1}, 12 kg dual-disc transient module showed that torque smoothing, and zero battery transients can be achieved in urban cycles. These prior findings motivate the present study, in which the same two architectures are re-examined under harmonized test conditions to isolate the influence of flywheel inertia, gear ratio and control strategy on overall energy recovery and to quantify the incremental range benefit relative to conventional battery-dominant systems.

The studies develop a thermoelectric-pv hybrid energy system consisting of two thermoelectric generators for use in hybrid electric vehicles. This system is capable of dynamically charging the battery of the hybrid vehicle by converting the heat generated by solar radiation and the hot air expelled into electrical energy [7]. Consequently, this new waste heat recovery system achieved a maximum power output of 350 W under the condition that exhaust gases raised the temperature of the heat pipe evaporator's surface to 170 °C. [8]. And another aspect is that energy harvesting is a science that collects energy from the surrounding environment and converts it into more useful forms of energy (such as electrical energy). This is a prominent and crucial emerging technology that may serve as a solution to ensure the supply of environmental energy and thereby extend the lifespan of low-power electronic devices [9].

Recent studies have explored various methods to enhance the efficiency of waste heat recovery systems, particularly for low-grade heat sources. Jiménez-García et al. (2023) reviewed Organic Rankine Cycle (ORC) configurations and emphasized the benefits of advanced layouts, such as hybrid and recuperative designs, over conventional simple cycles [10]. They also examined trans critical CO_2 power cycles and highlighted the role of cycle architecture, particularly reheating and recuperation, in improving performance at different temperature ranges. In addition, Rodríguez-de Arriba et al. (2022) investigated CO_2-based mixtures and demonstrated their potential to reduce system irreversibility and improve exergy efficiency [11]. These studies collectively indicate that both cycle optimization and the choice of working fluid are critical for improving the performance of low-grade heat recovery systems. The present work aims to build on these insights by evaluating selected approaches under relevant thermal conditions.

Research demonstrates that electric turbochargers significantly improve transient response compared to conventional systems. Katrasnik et al. [4] showed a reduction in the time required to perform a transient power increase for a diesel engine. Similarly, Ibaraki et al. [5] achieved a reduction in response time and an increase in low-speed torque using a motor assist. Furthermore, Millo et al. [6] reported potential fuel consumption reductions in transient-heavy urban cycles.

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However, these studies primarily present numerical results or specific tested configurations, and a key challenge remains the parasitic energy loss from the electrical power required for motor assistance, which can decrease efficiency gains. Research will mainly focus on exploring solutions like integrated motor-generators acting as both motors and generators to restore energy, reducing this loss and further improving overall system efficiency.

This paper will use overall efficiency as a primary criterion to evaluate and compare several energy recovery methods, with the goal of identifying the most practical and effective solution for capturing and reusing waste energy in automotive vehicles to enhance fuel economy and extend travel range. The analysis will also consider technical feasibility and integration potential within existing vehicle systems.

2. Regenerative breaking

Regenerative braking is an energy recovery technology that converts the kinetic energy generated during vehicle deceleration or braking into storable electrical energy, rather than dissipating it as waste heat through traditional friction braking systems.

Through simulations conducted on a range of vehicle types as shown in Figure 2, the results demonstrate that, under the WLTC driving cycle, this control strategy can reduce energy consumption by 29.5% to 30.3% compared to the same vehicles without regenerative braking capability [12].

Regenerative braking systems not only capture energy that would otherwise be lost during deceleration but also contribute to lower vehicle emissions and reduced brake wear. By conserving fuel and minimizing material degradation, these systems offer financial advantages. Additionally, their implementation supports environmental sustainability and the advancement of renewable energy technologies [13].

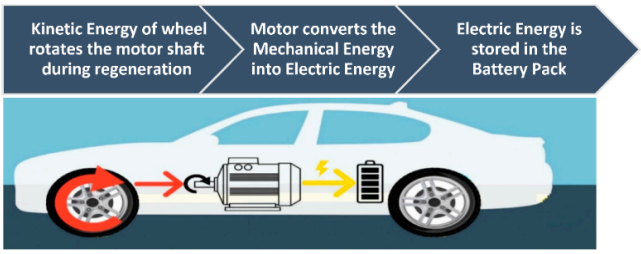

Figure 1. The principle of regenerative braking [14]

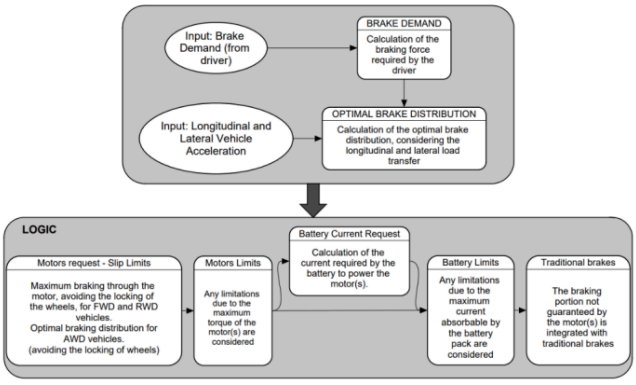

Figure 2. The process steps of braking recovery [12]

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In one CTCRDC cycle, serial 2 got back 0.267 kW·h of energy. This was more than serial 1 (0.235 kW·h) and parallel (0.206 kW·h). Serial 2 also did better in terms of axle efficiency (0.4385), battery charge-discharge efficiency (0.8197), and vehicle energy efficiency (16.436 kW·h/100 km). It also had the highest contribution rates: 41.09% for energy transfer efficiency (σr) and 24.63% for driving range (σc). The discussion says serial 2 is better because its regeneration setup is more active. This means it gets back when the car slows down. Better coordination between regenerative and friction braking helps improve energy recovery. The conclusion shows that the proposed evaluation parameters (σr and σc) work well for checking RBS's contribution. It confirms that serial 2 has the highest regeneration efficiency. These findings can help make regenerative braking systems in EVs better.

In the US06 drive cycle, we used the combined method of pole changing and over fluxing. This method led to an energy consumption of 92 kJ. It was much lower than the 96 kJ of pole changing alone, the 108 kJ of four-pole mode, and the 127.8 kJ of two-pole mode as shown in Figure 3. Its regenerative efficiency stood at 43.26%. This was higher than the 35.8% of two-pole mode and 34.8% of four-pole mode. Test results also matched simulations, showing a 23.3% reduction in energy use. The discussion found that pole changing can extend the range of constant power. Over fluxing, in turn, can enhance energy capture at lower speeds. This brought the low-speed cutoff down from 670 r/min to 350 r/min. It also balanced torque, speed, and losses effectively. This study shows that combining pole changing with controlled over fluxing improves regenerative braking efficiency. It reduces energy consumption by about 25%. Key outcomes include a longer constant power range, a lower cutoff speed, and better energy recovery. This not only eases "range anxiety" in EVs. It also shows that multiphase pole-changing motors, with such combined techniques, can be a promising option.

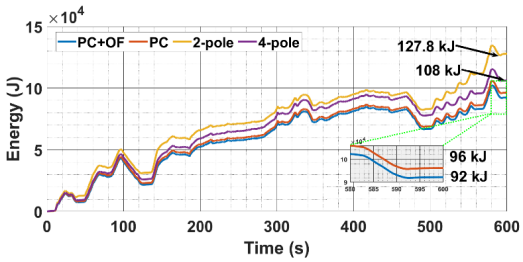

Figure 3. Energy consumption in the full cycle for two-pole, four-pole, pole-changing, and overfluxing in pole-changing mode [15]

In the context of global efforts to promote sustainable transportation methods, promoting the energy efficiency of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has become a key focus of academic research. Among them, regenerative braking systems (RBS) and energy-based path optimization strategies are regarded as crucial means to improve energy efficiency. This study focuses on the influence of vehicle characteristics (such as vehicle weight) and road environment (such as slope changes) on energy consumption performance, aiming to identify the core variables that can be used for energy-saving route planning in navigation systems, thereby addressing the shortcomings of current mainstream navigation systems that generally prioritize travel time or distance while neglecting energy consumption optimization.

To achieve this goal, the research was conducted in the city of Gdynia, Poland. A Mazda MX-30 electric vehicle was selected as the experimental platform as shown in Table 1. During the experiment, the speed and altitude data of the vehicle during driving were collected using a global positioning system device, and four test routes were selected as shown in Table 2.

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The research focused on analyzing the effects of different load conditions (respectively 100%, 125% and 150% of the base mass) and changes in road gradients (0%, 100% and 200% of the height variation) on the energy efficiency coefficient (EEC). The research was based on the following premise assumption: Variables such as road gradients and vehicle mass have a significant impact on energy consumption performance. If these variables are incorporated into the navigation algorithm, it is expected to achieve more energy-efficient path selection.

Table 1. Driving system parameters of the vehicle under test [16]

Vehicle	Mass (driver inc.) [kg]	Power [kW]	Battery capacity [kWh]	ηel [%]	ηreg [%]	Paux [W]
Mazda MX-30	1795	107	35	78	61	200

Table 2. Route specifications [16]

Route No.	Length [m]	Av. speed km/h	SEC [kWh/ (t·100 km)]	RBSE [kWh/ (t·100 km)]	Height min [m]	Height max [m]	Height differ-ence [m]
1	2762	16	10.7	5.3	41	88	20
2	2931	26	8.5	4.5	40	67	0
3	3117	35	6.6	1.9	45	57	–2
4	2891	45	6.2	3.6	33	59	–21

3. Mechanical flywheel

A flywheel is a mechanical rotating energy storage device that stores kinetic energy in the form of rotational inertia [17]. The flywheel stores energy as rotational kinetic energy and releases it during acceleration [18]. In contrast to electrochemical batteries, which store energy in chemical form and experience limited charge or discharge rates and degradation under high current pulses, flywheels store energy mechanically in a spinning mass [19]. As shown in the Figure 4 and Figure 5, when applied to electric vehicles, flywheels smooth high power transients during acceleration and braking, lowering peak battery currents and increasing overall energy efficiency [20].

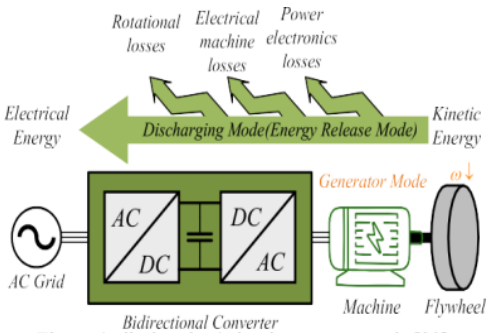

Figure 4. Discharging/releasing energy mode [20]

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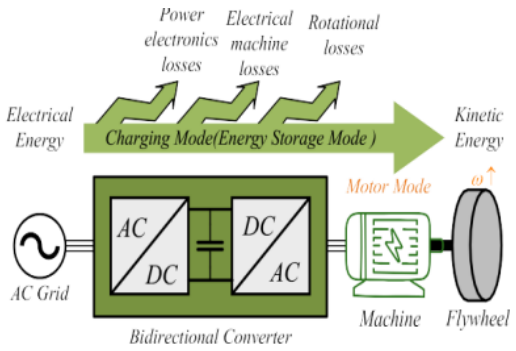

Figure 5. Charging/storage energy mode [20]

Recovering kinetic energy during vehicle deceleration is one of the important ways to improve the energy efficiency of transportation. Especially for electric and hybrid vehicles, the driving range is still a crucial issue [21]. Conventional battery-based regenerative systems suffer from significant efficiency losses due to chain inefficiencies in energy conversion (mechanical → electrical → chemical) and limited charge acceptance rates during short-duration braking events. Mechanical flywheel energy storage system (FESS) provides an alternative way to store the kinetic energy in form of rotational inertia without involving electrochemical conversion process [20]. This paper aims at investigating the improvement of overall energy recovery efficiency with flywheel-based KERS by comparing with battery dominated system, especially for high power transient braking with less energy conversion.

Validate the conjecture by large-quantity experiments, and conduct simulation experiments by constructing physical prototypes as shown in Figure 6. Validate that the net energy exchange between the flywheel and the battery emulator (DC bus capacitor) is zero during vehicle acceleration. The steady DC bus voltage and the measured energy increment validate the minimal cell participation and high mechanical transmission efficiency in practice, to validate the crucial role of the mechanical flywheel in energy recovery. The suggested 4WD electric powertrain with flywheel KERS improves significantly the kinetic energy recovery efficiency by reducing electrical energy conversion losses.

As shown in Figure 7, the wheel-to-wheel ROR is improved to 0.75 PU compared to 0.36 PU in conventional battery-based systems, when 70% of the braking energy is transferred mechanically to the flywheel with 95% efficiency and only 30% is converted electrically. This lessens the dependence on battery power during acceleration or deceleration, allowing for zero-battery usage when flywheel speed is greater than wheel speed ($\omega FW \geq \omega W$).

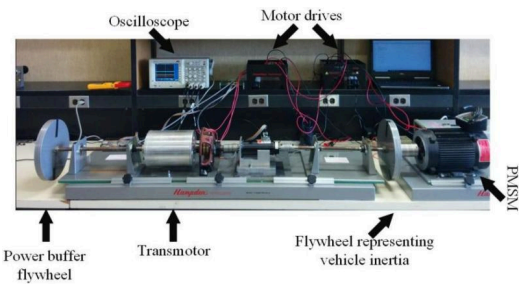

Figure 6. Physical prototypes [6]

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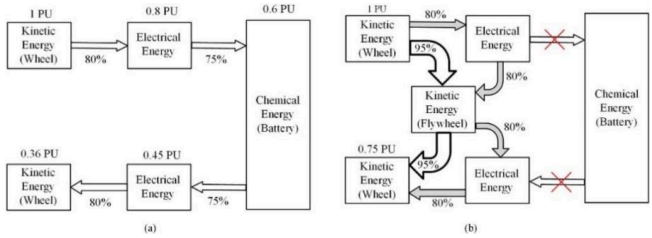

Figure 7. Direct energy utilization (a) Conventional electric powertrain (b) Powertrain based on flywheel system [6]

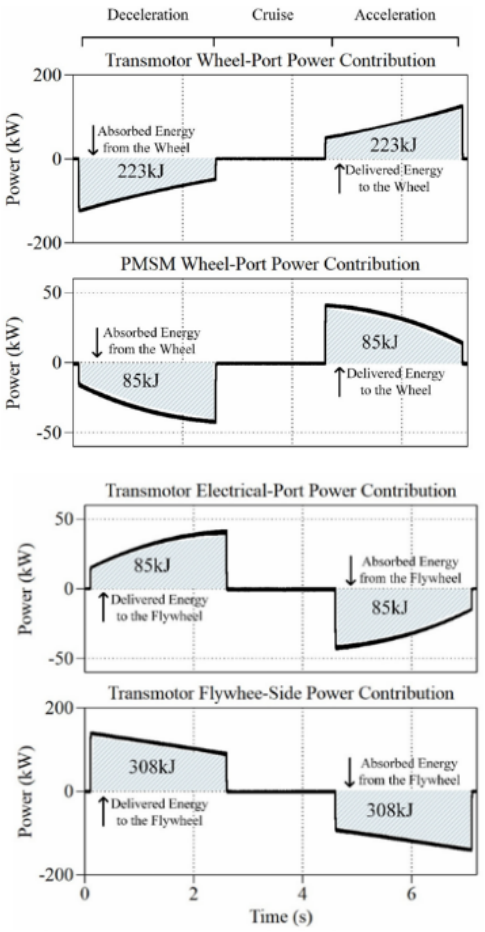

Figure 8. KERS power and energy demands [6]

Figure 8 the experimental verification showed that the powertrain can handle 150 kW of mechanical power, three times its electrical rating (50 kW), without overloading any components, thanks to the magnetic clutch function of the Transmotor. Thus, the flywheel system increases the life of the battery by decreasing the number of charge cycles, and improves overall efficiency by 8-10% in urban driving cycles, overcoming the main disadvantages of conventional regenerative braking. The objective of this study was to improve the regenerative braking efficiency of electric vehicles through the design of a non-ultra-high-speed electromechanical flywheel hybrid system based on planetary gears [5], so as to solve the problem of energy loss of the vehicle under the application scenario of frequent urban stop-and-go. The topology of the flywheel unit is optimized such that the speed-regulating motor is connected to the sun gear, the flywheel is connected to the

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ring gear, and output is to the planetary carrier, which helps maximize torque transmission and minimize mechanical losses. As shown in the Figure 9, the validation conjecture employs a test platform with an electric dynamometer and a battery simulator to mimic the driving cycle in each scenario [5]. The experiment validates the function of the flywheel in smoothing battery power variation under NEDC cycles.

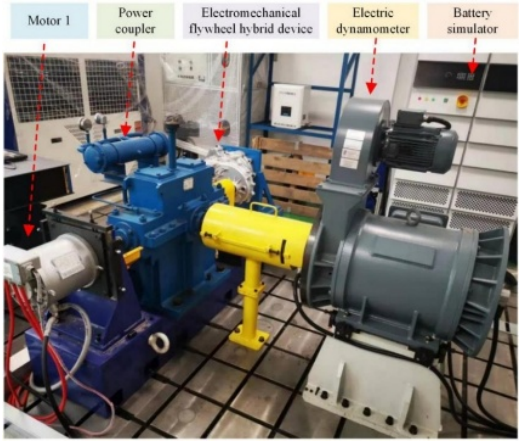

Figure 9. The platform used to validate [4]

Figure 10, the fluctuation of battery power is mitigated by 53.8% with the buffering of flywheel. The flywheel hybrid system alleviates the peak battery current and changes the motor working area into the high-efficiency zone, as shown in

Figure 11, which leads to an increase in powertrain efficiency by 8.2% (J1015), 5.6% (NEDC) and 4.3% (HWFET). The fast energy buffer of the flywheel decreased 0-100 km/h acceleration time by 18.25%, and reclaimed 2704.62kJ braking energy, which extends driving range by 15.43%. More importantly, the lithium battery becomes 6.7% efficient due to less high-current stress and deferred degradation. The study concluded that the optimized flywheel parameters (300 m/s rim speed, 0.7 radius ratio) balance safety and cost while covering 94% of braking events, making mechanical energy recovery indispensable in improving the efficiency of urban electric vehicles.

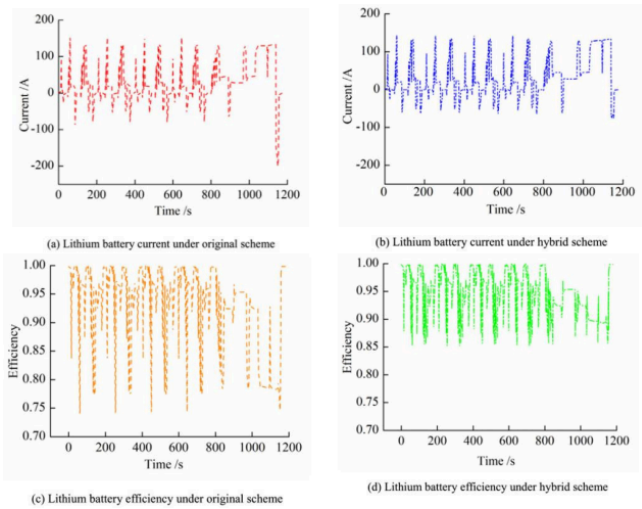

Figure 10. Comparative experiment between original and new under NEDC [5]

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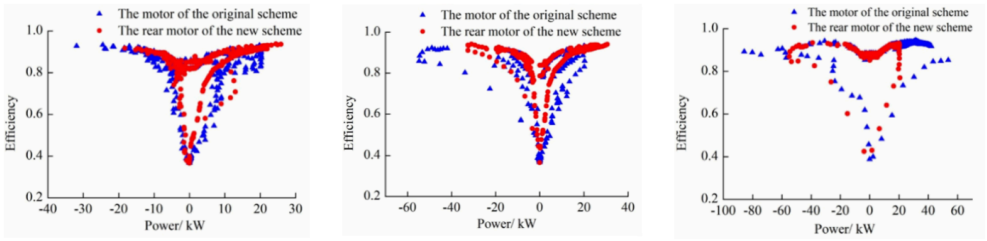

Figure 11. Difference between original and new [5]

4. Thermoelectric

The thermoelectric system is an indispensable part in energy recovery. It can convert waste energy into new power through a thermoelectric engine to improve the commuting efficiency or operation efficiency of vehicles. Analysis and simulation of the thermoelectric generator, as shown in Figure 12. The results show that the efficiency varies between 65.83% and 67.1%. Considering the weak thermoelectric performance of the modules available in the market, this is quite encouraging [22]. The thermoelectric system can also reduce electricity consumption. The waste heat and mechanical energy available on the highway can be converted into electricity, which can enhance the overall efficiency of the engine and improve performance, as shown in Figure 13. Ultimately, the commuting distance can be extended [23].

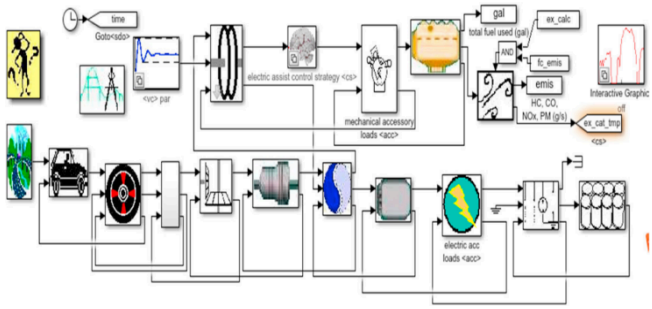

Figure 12. Analysis and simulation of the thermoelectric generator of hybrid vehicles [22]

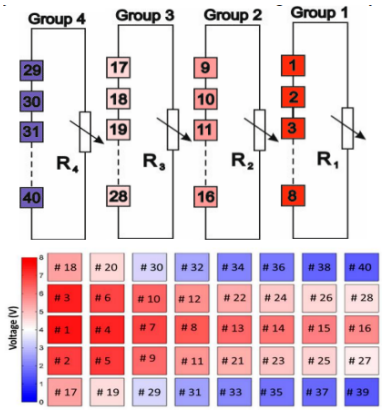

Figure 13. In the different heat, mechanical energy convert into electricity [23]

In the current energy usage pattern, it is necessary to recognize various different forms of energy, including chemical energy, electrical energy, mechanical energy and thermal energy. Utilizing

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thermoelectric generators (TEGs) to exploit the untapped potential of waste heat, particularly that from hybrid vehicle exhausts. The aim of this project is to conduct an in-depth study on the complexity of this technology, with a particular focus on the efficiency of the teg in converting the waste heat from vehicle exhaust into usable electrical energy. To conduct the module test, thermal and electrical contact resistances need to be taken into account. Since this module is composed of multiple thermocouples, it is necessary to ensure that its size conforms to the design for exhaust as well as the design (shown in Figure 14). By modeling this module, the maximum potential for generating electrical energy through thermoelectricity can be exploited. As the thermoelectric module is a sensitive component, careful modeling can prevent unnecessary damage.

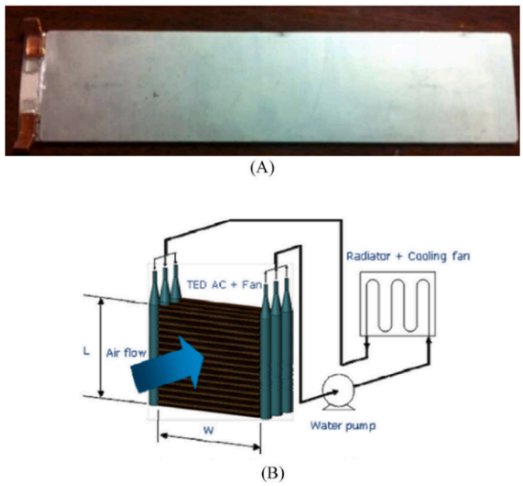

Figure 14. The working principle of thermoelectric generators (TEGs) [24]

The temperature in the laboratory is maintained within the range of 20 to 25 degrees Celsius, and the environmental pressure is the standard atmospheric pressure. All experiments are based on simulating battery modules and mainly compare and analyze three cooling methods: natural air cooling, pure liquid cooling, and mixed liquid-air cooling. The research focuses on the thermal behavior of the battery under natural air-cooling conditions under different voltage supply conditions. The experimental results show that as the supply voltage increases, the increase in the internal temperature of the battery and its change rate significantly increase. When the heater voltage is raised from 30 volts to 60 volts, the stable temperature achieved by the system almost doubles, and the specific change trend is shown in Figure 15. Subsequently, the researchers evaluated the proposed liquid cooling and mixed thermoelectric liquid-air cooling systems. Under the reference voltage of the heater at 40 volts, the mixed cooling system shows better heat dissipation performance compared to pure liquid cooling, and its effect is also superior to natural air cooling. In addition, to prevent equipment corrosion, a copper shell was added to the system.

This battery system can reduce the corrosion problems caused by coolant. Relevant experiments have been conducted in practical applications. The experiments were carried out in an air environment and also in water.

In aerial conditions, the experimental data revealed that the temperature variation closely mirrored that of the control group without thermal protection. Underwater testing demonstrated that the hybrid thermal management system also experienced a notable decline in temperature. Future studies will prioritize battery packs with more stringent cooling requirements. Additionally, a computational thermal model will be developed and analyzed to facilitate numerical simulations and the refinement of design parameters.

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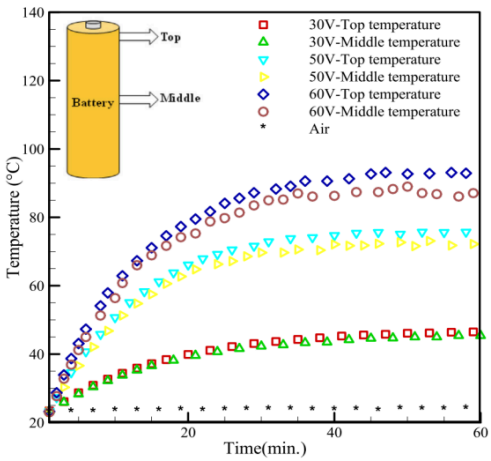

Figure 15. The voltage from 30 volts to 60 volts [25]

To mitigate global warming, automotive manufacturers must transition to cleaner, more sustainable hybrid vehicles. A key strategy for reducing fuel consumption involves integrating renewable energy solutions, such as a thermoelectric-photovoltaic (TE-PV) hybrid energy system. This system combines two TEGs—a hot-spot engine and a photovoltaic (PV) generator—to dynamically charge hybrid vehicle batteries by harnessing solar radiation and waste heat from a vortex tube. The STEG comprises multiple modules distributed across the vehicle's sun-exposed surfaces and the vortex tube outlet. At the tube's exit, hot and cold air streams are separated, with a temperature differential ΔT of ~200°C. These streams are channeled to the hot and cold sides of the STEG, sustaining a high ΔT for efficient energy conversion. The thermoelectric effect, achieved through P-N doped semiconductor pairs, facilitates this heat-to-electricity conversion, as shown in Figure 16. The temperature at the STEG's hot and cold ends varies with vehicle speed. When stationary, the system reaches peak temperatures, which then decline and stabilize during motion, as shown in

Figure 17. The conversion efficiency depends on the ΔT across the STEG, which is influenced by ambient temperature and solar irradiance, as shown in Figure 18. At 33.33 m/s, recorded values include: the hot side is 76.1°C and the cold side is 2.1°C, the Output is 0.7742 A, 46.85 V, 36.27 W. Validation against mathematical models of analogous systems confirms consistent performance trends. Future research should focus on integrating STEG modules into the vehicle body to minimize aerodynamic drag and prevent additional fuel consumption.

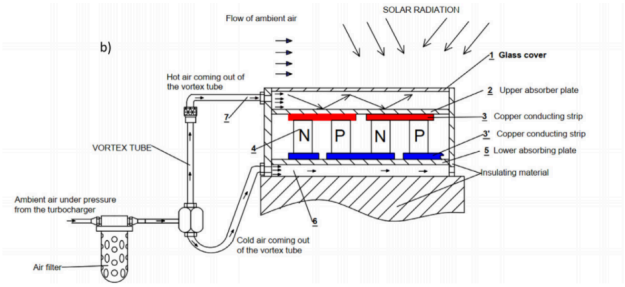

Figure 16. The STEG generator of heat-to-electricity conversion with P and N [7]

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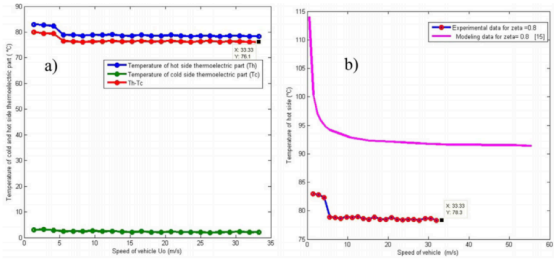

Figure 17. a: The temperature parameters of the hot and cold side b: The experimental data for hot side [7]

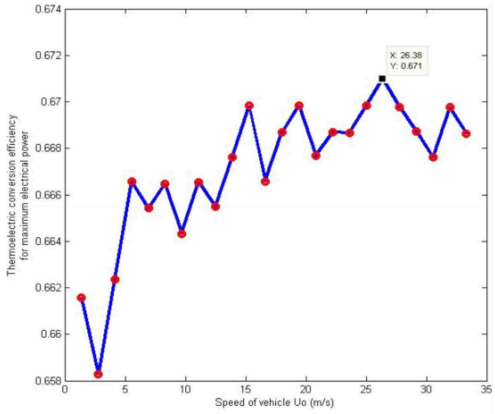

Figure 18. The relation of speed and thermoelectric conversion in vehicle [7]

5. Rankine cycle

The Rankine cycle is a thermodynamic process, which is generally used in power generation to convert heat into mechanical work. It operates by circulating a working fluid—typically water—through four main components as illustrated in Figure 19 a condenser [26], a pump ,an evaporator with an included superheater to add heat and produce steam [27], the steam is used to run the turbine in the expander which powers the generator . This closed-loop system is key to steam power plants, known for efficiently utilizing heat and reducing vehicle emissions. However, challenges remain in size, weight, and performance under variable engine conditions [28].

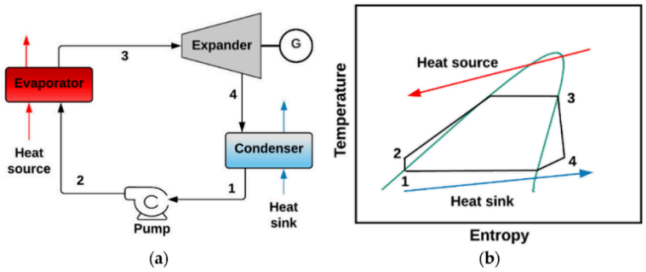

Figure 19. Simple ORC (a) System schematic; (b) T–s plot illustrating the energy and entropy transitions of the heat source and sink via arrows [28]

To recover waste heat and boost engine efficiency, the transcritical CO_2 Rankine cycle (tCO_2RC) replaces water with CO_2 operating above critical pressure [11,29,30]. As shown in Figure 20, a combined system uses S-CO_2 as the primary cycle and reuses exhaust heat via T-CO_2 and ORC sub-

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cycles. This integration maximizes both high- and low-temperature heat use, improving overall energy efficiency.

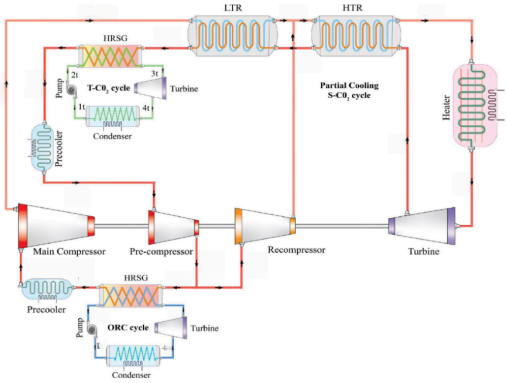

Figure 20. Diagrammatic representation of the integrated PC–TCO₂–ORC cycle [11]

This study evaluates five CO_2-based power cycles—Recompression (supercritical and transcritical), Partial Cooling, Recuperated Rankine, and Precompression—using exergy analysis. illustrates their operations through T–s diagrams, highlighting how key components interact to extract high-temperature heat (575–725 °C) [31]. Table 3 summarizes details optimal design parameters for comparing performance and identifying exergy loss sources.

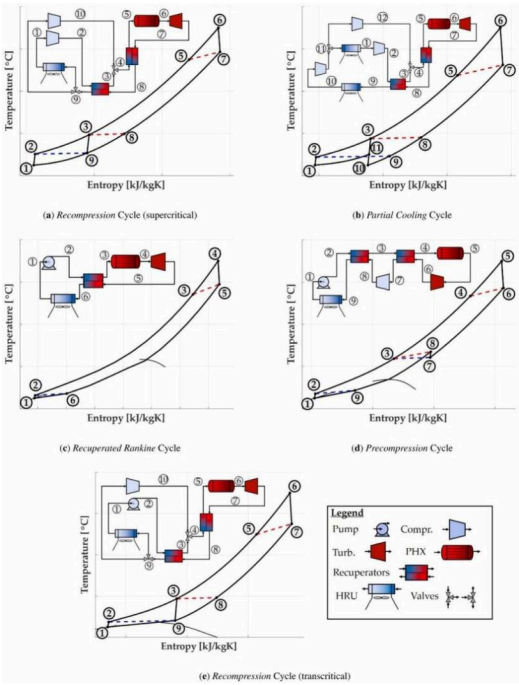

Figure 21. Configurations of the cycle analyzed for both pure (a, b) and mixed (c, d, e) CO_2 systems [31]

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Table 3. Optimal cycle parameters for all examined CO_2-based setups at source temperatures of 575°C and 725°C [31]

Acronym	Layout	Working Fluid	PRMC	ERT	PRPrC	α
$RCCO_2$	Recompression	100% CO_2	2.37 / 2.45	2.20 / 2.27	–	0.29 / 0.29
$PCCO_2$	Partial Cooling	100% CO_2	2.23 / 2.24	3.18 / 3.70	1.55 / 1.80	0.40 / 0.41
PrCD1	Precompression	85%CO_2/15% C_6F_6	3.22 / 3.22	3.91 / 4.20	1.31 / 1.41	–
RRD2	Rec. Rankine	83%CO_2 /17% $TiCl_4$	2.60 / 2.60	2.47 / 2.47	–	–
RCD3	Recompression	80%CO_2 / 20% SO_2	3.16 / 3.16	2.93 / 2.93	–	0.38 / 0.38

Rodríguez et al. [11] studied how CO_2 mixtures enhance the efficiency of transcritical Rankine cycles for low-grade waste heat recovery. The results in Figure 22 show that pure CO_2 achieves 65–75% exergy efficiency [32],while mixing it with C_6F_6 or $TiCl_4$ raises efficiency above 90% as dopant concentration increases. In contrast, SO_2 blends reduce efficiency to around 60%. These mixtures also lower exergy losses in typically inefficient components like the evaporator and gas cooler [33,34]. Despite concerns such as flammability, the study confirms the strong potential of CO_2 mixtures for improving cycle performance.

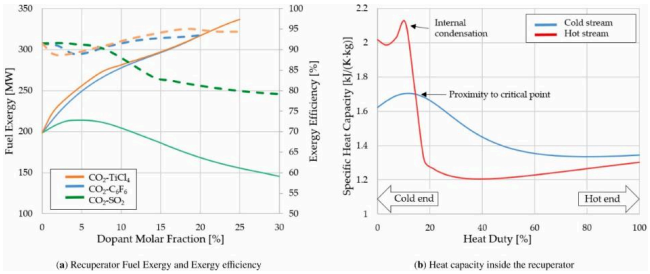

Figure 22. (a) Fuel exergy (solid) and exergy efficiency (dashed) of the recuperator versus molar fraction for C6F6, TiCl4, and SO_2; (b) Specific heat [kJ/(kg·K)] of the hot and cold streams in the recuperator, based on an 85% CO_2–15% C6F6 mixture [11]

To optimize fluid performance, Wang et al. [35] introduced a heat-matching method that adjusts the dryness point at the evaporator outlet, isolating fluid effects. In a fixed exhaust subcritical Rankine system, pinch-curve analysis. ensures optimal heat exchange. Under constant turbine inlet conditions, ammonia outperforms R123 and R245fa, delivering around 9.69 kW output and about 5.2% higher thermal efficiency due to better heat matching and less exergy loss, as shown in Figure 23.

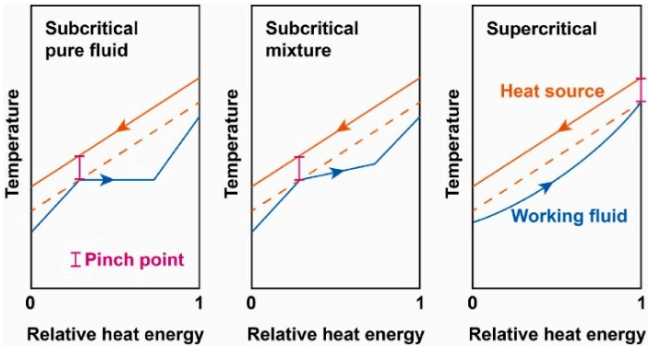

Figure 23. Pinch point in the T-Q diagram [35]

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Figure 24 confirms ammonia's advantage over R123 and R245fa, supported by Patel et al. [36] , who linked improved thermal matching to efficiency gains. Despite minor pressure drop penalties (<5%), compactness is retained. The study concludes that precise control of evaporation dryness and fluid selection significantly improves Rankine cycle efficiency under fixed boundary conditions.

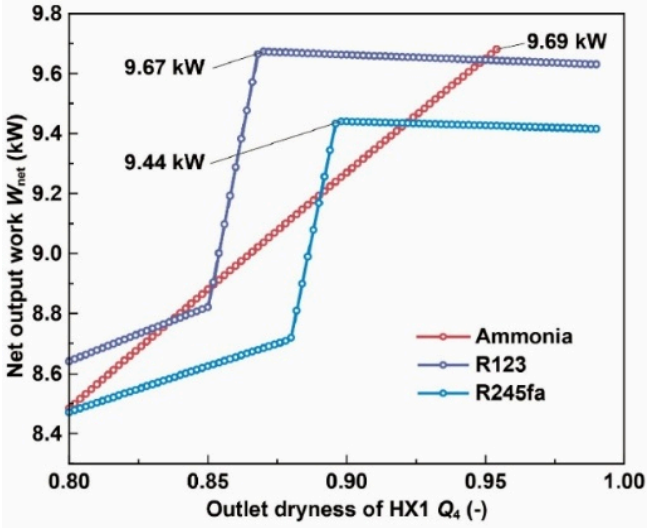

Figure 24. Variation of net output power (W_{net}) for ammonia, R123, and R245fa as a function of Q_4 [36]

6. Electric turbochargers

An electric turbocharger is a force induction system that produces extra power by intaking more air during combustion, which combines a normal turbocharger with an electric motor attached to the turbo shaft. Figure 25 shows the structure of the electric turbocharger, where the compressor, turbine, and the motor are connected by the turbo shaft [37]. The compressor draws air in and compresses it and delivers it into the fuel cell. The fuel cell then signals the motor to spin, allowing the turbocharger to intake more air. This will increase the waste energy the turbine can regain and use when humid air is exhausted, which can be used to create more power.

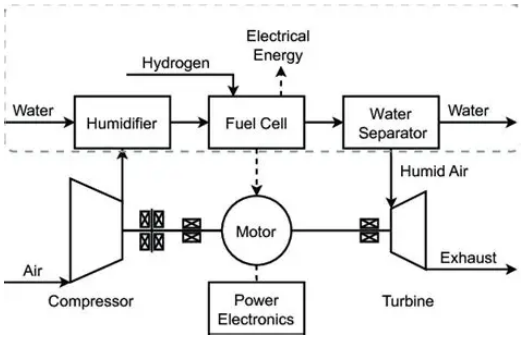

Figure 25. The structure of an electric turbocharger [37]

Electric turbochargers improve the maximum power output of the fuel cell system by recollecting and utilizing waste energy from exhaust, but condensation can be a potential problem that affects the efficiency of energy recovery. This study mainly focuses on how condensation impacts the working stability of the turbine and compressor. The areas that will be running Computational Fluid

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Dynamics (CFD) virtual tests are demonstrated in Figure 26. By running these tests, the turbine performance diagrams in humid air are created. They are later used to construct reduced-order models (ROM) based on Aircraft Engine Simulation for Transient Operation Research (ASTOR) [37] to simulate the different conditions of the vehicle. This include acceleration and deceleration, as well as the steady position where all parameters are likely to remain constant. During this process, the effects of condensation on energy recovery of the electric turbocharger will be projected.

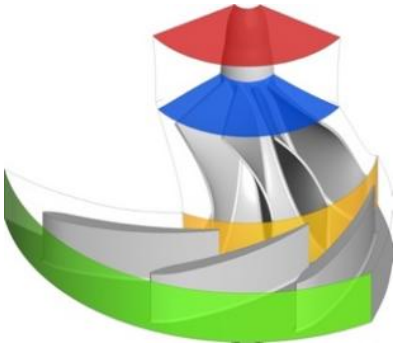

Figure 26. CFD areas [37]

Condensation in the turbine slightly reduces the overall efficiency of the system by 0.1%. In the case where no extra pressure is added, the maximum power output is 77% of the estimated power in the test. By using an electric turbocharger, the power output has improved 7.2% compared with a normal turbocharger. Despite the negligible effect of condensation on efficiency, it still created risks in stability of the system during transient operations. In addition, when the vehicle is decelerating, the surge margin of the compressor decreases up to 12% as shown in Figure 27, where it can lower to 8% [37]. This may cause safety problems in operating the system, leading to lower working efficiency of the electric turbocharger, as the rate of energy recovery may decrease. In the future, improving control systems and developing machines to work with high pressure level of turbine and compressor ratios is necessary to ensure the system's efficiency and reduce the safety issues.

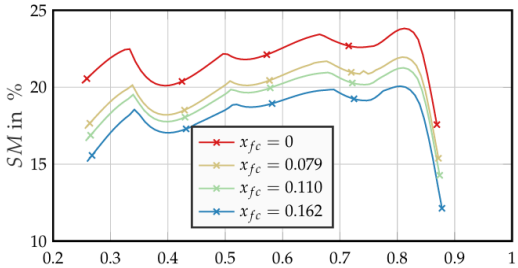

Figure 27. Surge margin of compressor based on equation for 4 water-to-air ratios [37]

Traditional turbochargers suffer from turbo lag and energy losses, which reduces the overall efficiency of the system. E-turbos are designed to recover energy from exhaust, improve responsiveness in transient operations, and reduce parasitic losses. By using an approved 1D model (GT-Power) of a 2.0L turbocharged SI engine [38] as shown in Figure 28, three steady-state periods in Figure 29 will be focused on. Firstly, the quantity of enthalpy loss will be assessed while relating to the turbine and compressor's size. Next, studies are made to suppress the wastegate and using electric turbocharger for boost control. Finally, the wastegate will be restored to control pre-turbine pressure and investigate the changes between the size of turbine and area of wastegate. Transient simulations and projections will further estimate and predict changes in efficiency during operations.

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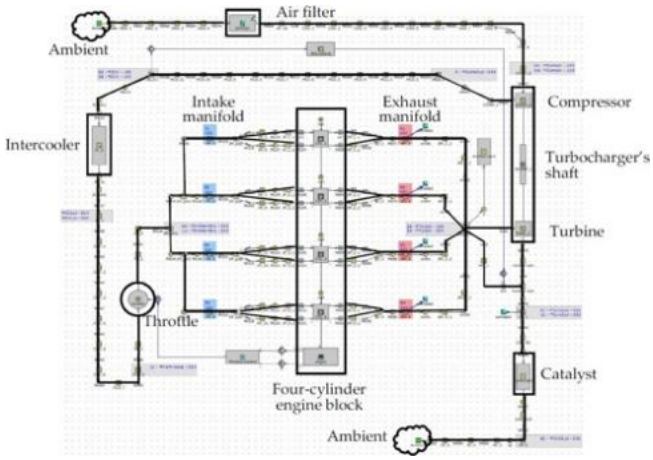

Figure 28. 1D model of the 2.0L turbocharged SI engine [38]

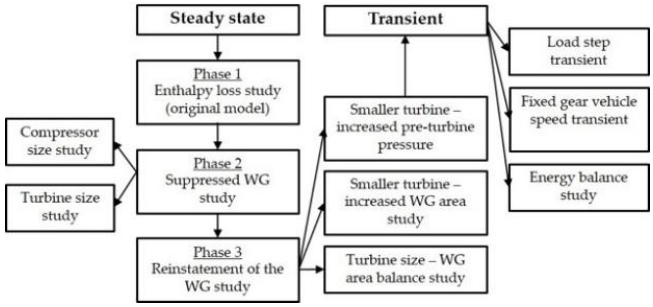

Figure 29. Simulation process flowchart [38]

Steady-state analyses reveal that a 10% smaller turbine with 5–15% increased pre-turbine pressure ensures energy harvesting across most operating points as shown in Figure 30. Figure 31 shows the increase in efficiency compared with the baseline engine, although there is existence of peak torque penalty. Driving cycles show net energy regeneration, with combined driving and US06 representing the maximum energy recovered as shown in Figure 32. Figure 33 balances component sizing to maximize efficiency. In the future, research and development in advanced turbine or compressor matching is in priority.

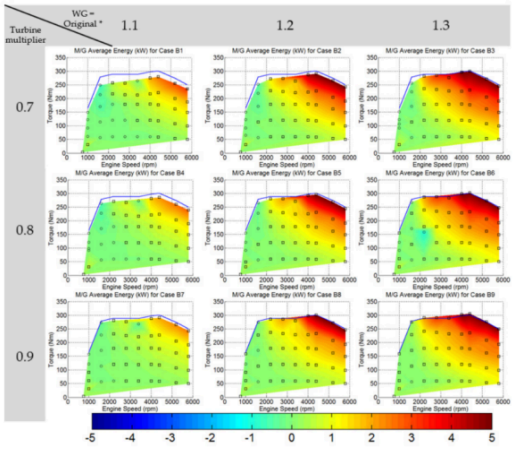

Figure 30. DoE analysis of average energy of the motor-generator for multiple pre-turbine pressures and turbine sizes [38]

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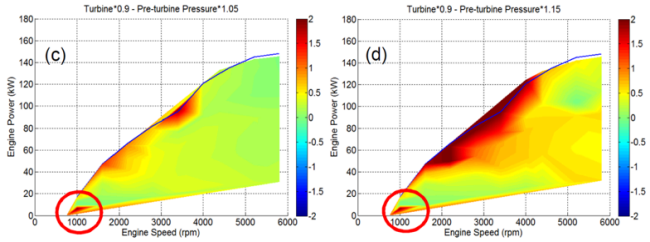

Figure 31. Absolute difference in the overall efficiency of two different models; the negative numbers represent loss in efficiency: (c) 5% increased pre-turbine pressure and 10% smaller turbine; (d) 15% increased pre-turbine pressure and 10% smaller turbine [38]

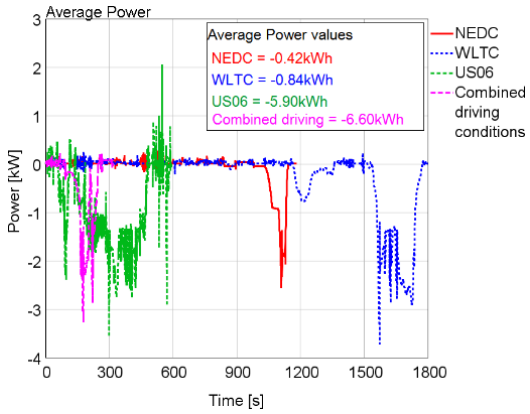

Figure 32. Average power given or received by the motor-generator; negative numbers represents energy harvesting [38]

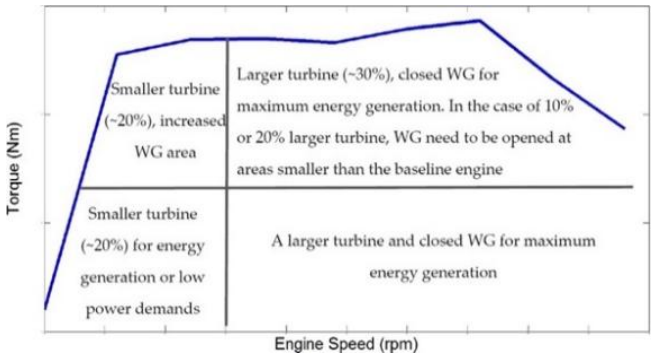

Figure 33. Optimal size of components for energy harvesting and maximum power output [38]

7. Conclusion

This paper systematically compared and evaluated five complementary energy-recovery strategies including regenerative braking control, flywheel buffering, auxiliary thermoelectric generators, Rankine waste heat utilization, and electric turbine compounding to discuss their applicability in extending vehicle range.

• Regenerative braking optimization using pole-changing, validated in MATLAB/Simulink under full torque mode and US06 cycle, achieved ~25% energy savings. Under CTCRDC, regenerative braking contributed 41.09% to energy efficiency and 24.63% to regenerative range.

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• Integrating a planetary gear flywheel into a four-wheel-drive buffer improved 0–100 km/h acceleration by 18%, raised interwheel energy return from 0.36 PU to 0.75 PU, cut battery current peaks, and increased powertrain efficiency by 6–8% across J1015, NEDC, and HWFET cycles. This subcritical 20 kr min^{-1} flywheel serves as the primary power reservoir, extending battery life and range.

• At 33.33 m/s, with a high temperature of 76.1°C and low of 2.1°C, the optimized STEG generated 0.7742 A, 46.85 V, and 36.27 W. The design more fully converts thermal and exhaust energy into electricity, increasing mileage with high efficiency. Integrating the STEG into the vehicle body could eliminate aerodynamic drag penalties, thus avoid extra fuel consumption and enabling practical application without compromising vehicle performance.

• CO_2/R134a blends in transcritical Rankine cycles improved net power output and efficiency by >20%, reducing exergy destruction and condensation issues.

• With a 10% smaller turbine, higher pre-turbine pressure, and motor assistance, the electric turbocharger cut transient response by 70–90%, harvested up to 6.6 kWh per driving cycle, and improved overall efficiency, with only a 5% maximum power penalty and fuel consumption increase of up to 1.8%.

Overall, all methods enhance system efficiency by reclaiming waste energy. The mechanical flywheel ranks highest for its robust, high-power-density storage, rapid response, and independence from battery cycling, making it ideal for urban EVs. Regenerative braking follows for its substantial efficiency gains and range extension with simple integration, though limited by braking opportunities and driving patterns.

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