A review on opportunities of thermionic regeneration system in hybrid electric vehicle

K Kodihal, A Sagar
School of Automotive Skills, Bhartiya Skill Development University, India
E-mail: kantaprasad.kodihal@ruj-bsdu.in

Abstract. A hybrid electric vehicle utilizes power from both engine and battery to drive the wheels. Hybrid electric vehicle architectures are micro, mild, full and plug in hybrids. This review covers recent optimization in technologies and systems of hybrid electric vehicle. It is evident from the literature that utilizing waste energy such as braking losses for battery charging is more effective for micro and mild hybrid electric vehicle. The increase in electrification increases the demand of alternate battery charging methods in vehicle. Therefore, the opportunity lies in recovering waste heat of engine for battery charging. This could be done by direct energy converters such as thermoelectric and thermionic converters. The paper comprehensively studies these direct energy converters on the basis of their working principle and conversion efficiencies. The results from this study show that thermionic energy conversion stands better for hybrid electric vehicles as compared with other direct energy conversion methods.

1. Introduction
The statistics on country-wise petroleum consumption during the years 2000-2014 shows India as the third largest consumer of petroleum, consuming about 3.9% of world’s petroleum reserves [1]. Due to harmful environmental effects the use of fossil fuel in the vehicles is a rising concern. Combustion of these fuels in automobiles generates gases like CO2 which enhance global warming. The CO2 measurement system developed by Earth System Research Laboratory, Colorado observed an increase of 11.5% in global atmospheric CO2 in the past decade [2].

Hybrid electric vehicles classified as mild or micro hybrids, full hybrids and plug in hybrids. The vehicle can be of series or parallel configuration. It is important to improve the performance of a hybrid electric vehicle. The future development of transportation will be in hybrid electric vehicles. Reducing the manufacturing cost and the overall system with the use of innovative scientific research can increase hybrid electric vehicles share in market. This could be achieved by utilization of waste energy as an alternate battery charging method.

Recent automotive research is focused on development of a thermoelectric generator which uses seeback effect to convert heat to electricity directly. Thermoelectric material has hot side, cold side and heat exchangers. Engine’s coolant or exhaust waste heat can be converted into electricity. Lost energy is thus reclaimed; thermoelectric generator can decrease fuel consumption by the reducing electric generator load on the engine. Similarly, thermionic energy conversion is a direct energy conversion method. This
works on thermionic emission principle. The Richardson-Dushman has derived an expression for calculating the energy output of thermionic converter. The thermionic converter uses anode and cathode as working members. Cathode when gets heated to working temperature, emits electrons. These electrons are travelled to the anode through a vacuum or gas, this causes current to flow. The thermionic converter holds best application in space and terrestrial.

2. Hybrid Electric Vehicle

Hybrid vehicles combine two or more technology principles to produce, store and deliver power. Hybrid Electric vehicles are basically of two types; series (Engine charges battery and only electric motor drives wheels) and parallel (both engine transmission and electric motor can drive the wheels simultaneously). When the energy consumption and performance criteria of conventional vehicle are compared with series hybrid vehicle and parallel hybrid vehicle it shows that, in the fuel consumption comparison, especially at the urban drive cycles, plug in hybrid electric vehicle and series hybrid electric vehicle consequently are better than conventional vehicle. Hybrid electric vehicles are seen as good alternatives for conventional vehicles. [3]

![Figure 1. Hybrid electric vehicles.](image)

2.1 Battery management system

Various technologies are applied for the management of power based on software’s including online Power Management Controller, offline Power Management Controller, Rule-based Power Management Controller, Learning based, GPS based, Low level hardware based, Conductive and inductive charging are used. [4]. Recent trend shows the use of Lithium–ion batteries over lead acid batteries is more suitable. Also the power management control of lithium-ion battery is easier. Based on the specific situation, different strategies should be applied to improve and optimize the performance of Battery Management System in Electric Vehicles [5]. The key issues for lithium-ion battery management in Electric Vehicles (EVs) are Cell voltage measurement (CVM), Battery states estimation, Battery uniformity and equalization and Fault diagnosis.

These issues can be addressed by applying different methodologies/techniques like State of Charge (SOC) estimation, State of Health (SOH) estimation, and State of Function (SOF) estimation [10]. The charging method may be by plug in charging or regeneration from energy losses from the vehicle. Conventional vehicle emits 200-250 g CO2/Km. whereas, the carbon intensity of the Electric Vehicle is 135.6 g CO2/Km and that of the plug in hybrid electric vehicle (PHEV) is 81.9 g CO2/Km. It is evident that electric vehicles are a good solution only if they deploy renewable source of power generation for charging electric vehicle batteries, whereas emissions savings are greater for plug in hybrid electric vehicle than Electric Vehicles when the grid CO2 intensity is high [6].

Chassis roller dynamometer test shows that the dispersion of miles per gallon values for hybrid electric vehicles (HEVs) are larger than that seen for conventional gasoline vehicles. Therefore, the Hybrid
Electric Vehicles can tackle the demand of less emission and better fuel economy [7]. Hybrid Electric Vehicle system level design needs to be optimized. Optimization can be done by algorithms combined on multi-level to find the best design for given targets and constraints [8].

Hybrid Electric Vehicles (HEVs) reduce fuel usage by using electric storage systems to save part of the energy produced by the engine and other regeneration methods. Hybrid vehicle fuel efficiency is depending upon the effective utilization of engine and battery power. Probabilistic driving route prediction system is trained using Inverse Reinforcement Learning (i.e. learning an agent's objectives, values, or rewards by observing its behavior) for improving the fuel efficiency of the hybrid electric vehicle. The inverse reinforced learning saves 1.22% overall energy usage [9]. Hybrid vehicle applications are currently making their first steps in the global market. An experiment for enhancement of plug in hybrid electric vehicle includes methodology like Predictive control by Location Information, reducing demand charges while vehicle is parked, maximizing battery cycle life. It can be noted that practical algorithm can improve the predictive and operating conditions of a vehicle [10].

Various experiments are being performed to quantify gaseous pollutant emissions and fuel consumption of mild hybrid electric vehicle and full hybrid electric vehicle. Driving cycle test on Chassis roller dynamometer, Constant Volume Sampling (CVS) Technique for fuel economy and emission measurement respectively were used for experimental work. The Assessment and Reliability of Transport Emission Models and Inventory Systems (Artemis) measuring protocol gives actual driving cycle as compared to the standard European type approval procedure. For a correct measurement of Hybrid electric vehicle energy consumption and emissions, the battery’s state of charge (SOC) at the end of the test should be the same as in the beginning. Various options for ΔSOC correction have been proposed, like performing multiple measurements over every driving cycle in order to phase out the SOC variations, extending the test until ΔSOC becomes zero, and the graphical correction method. CO2 emissions were below 140 g/Km over almost all cycles tested [11]. Hybrid electric vehicle parameters and technologies powered by alternate and renewable energies are very important research interest of the researchers. The mathematical modeling and software simulations using MATLAB for hybrid electric vehicle can be the tools for conducting the research. An optimized integrated system for Management of available Power and energy is another approach for hybrid Electric Vehicle application [12].

2.2 Regeneration

Similarly, Research is under progress to enhance hybrid Electric Vehicles fuel economy and battery charging by using the techniques like constant acceleration during starting of the engine and regenerative breaking respectively were energy losses in breaking and acceleration are utilized for regeneration. A regenerative brake is a device which allows a vehicle to recapture and store part of the kinetic energy that would otherwise be 'lost' to heat when braking [13]. The regenerative braking system used in the vehicles satisfies the purpose of saving a part of the energy lost during braking. During test it is found that around 30% energy is recovered by the regenerative braking. The charging of battery from available alternate energy sources is still a less focused area for hybrid electric vehicle [14].

3. Hybrid Electric Vehicle Waste Heat Analysis

3.1 Calculations

Theoretically the calculation for internal combustion engine heat analysis is done by preparing Heat Balance Sheet. Heat balance sheet is a report of total heat supplied and heat lost in other systems. This test can also be conducted on engine test rig by measuring various engine operating conditions. Following are the formulae which can be used for heat balance sheet calculations of hybrid electric vehicles. Based upon assumptions a theoretical calculation for existing hybrid vehicles is done which shows falling result.
Table 1. Heat Balance Sheet.

| Description                                      | Formula                                                                 |
|--------------------------------------------------|-------------------------------------------------------------------------|
| Total Heat supplied                              | Heat supplied = \( m_f \times C \) KJ/min                               |
| Where,                                           |                                                                         |
| \( m_f \) is mass of fuel per minute             |                                                                         |
| \( C \) is calorific value of fuel               |                                                                         |
| Heat equivalent to break power                   | When power is given in KW                                               |
| \( P_b = KW \times 60 \) KJ/min                  |                                                                         |
| Heat carried away by water                       | Heat to cooling water = \( m_w \times c_{pw} \times (t_2 - t_1) \)      |
| Where;                                           |                                                                         |
| \( m_w \) is mass of water                       |                                                                         |
| \( c_{pw} \) is specific heat of water          |                                                                         |
| \( t_2 \) outlet temperature                     |                                                                         |
| \( t_1 \) inlet temperature                     |                                                                         |
| Heat carried away by exhaust                     | Heat to exhaust = \( m_g \times c_{pg} \times (t_{2g} - t_{1g}) \)     |
| Where;                                           |                                                                         |
| \( m_g \) is mass of air flow                    |                                                                         |
| \( c_{pg} \) is specific heat of gas/air        |                                                                         |
| \( t_{2g} \) outlet temperature of gas           |                                                                         |
| \( t_{1g} \) intake air temperature              |                                                                         |

Figure 2. Heat Losses from Hybrid Electric Vehicles.

4. Waste Heat Utilization

Intelligent energy utilization by an IC engine to convert heat into electricity by regeneration techniques are yet to be noticed. The optimal utilization of energy of the engine is very critical for the performance of an intelligent hybrid electric vehicle which can sense its surrounding. [15]

4.1 Thermoelectric Generators

Utilization of Internal Combustion engines waste heat for electricity generation can be one of the best approaches for regeneration. It is evident from the literature that the thermoelectric generation is a technique for recovery of waste heat by converting it into electric power. The most attractive ways to convert heat energy into electric power are Thermoelectric, Thermionic and Magneto hydrodynamic. [16]
The current methods used for automotive waste heat recovery systems include, energy conversion using thermoelectric generator (TEGs) and heat pipes. The maximum conversion efficiency by these methods is thermodynamically limited by the Carnot efficiency. Thermoelectric generator used for an IC engine’s waste heat recovery shows the conversion efficiency range in the range of 8-14.8%. The advantage of thermoelectric generator is that it reduces Break Specific Fuel Consumption by 6.2%. Most commonly thermoelectric devices are based on Bismuth telluride (Bi₂Te₃) because this material exhibits a relatively high figure of merit. [17, 18]

4.2 Thermionic converters
There are certain limitations associated with thermoelectric generators do have limitations such as low temperature limits and lower efficiency. Potential advantages of thermionic devices over thermoelectric devices in the ballistic transport regime are derived by calculating maximum achievable temperature difference for Bismuth telluride (Bi₂Te₃) as a function of length and comparing it with maximum achievable temperature difference for a device of the same length. Results show that thermionic device can operate significantly better than thermoelectric device. [19] Thermionic energy converters have generally been categorized into two types, which are the Vacuum Thermionic energy converters and the vapour Thermionic energy converters. Due to the lack of advanced fabrication techniques and technology development of thermionic energy converter is limited. By using advanced coating approaches, a low work function material, barium oxide (BaO), was deposited onto a polycrystalline-silicon carbide substrate, with a thin tungsten layer in between for adhesion purposes. Results show that low work function of 1.7 eV was obtained [20]
5. **Richardson Dushman Equation**

\[ j = A \cdot T^2 e^{-\frac{W_a}{kT}} \]  

Here, \( j \) is density of current of thermionic electrons.

- \( T \) is temperature of hot cathode,
- \( k \) is constant of the Boltzmann,
- \( W_a \) is work needed to extract an electron from the metal.

Direct conversion of heat into electricity has wide range of Space and Terrestrial applications i.e. Thermionic Energy Conversion. The research interest for thermionic converter is based upon development of novel grid structures for reducing space charge effect. David et al. Also suggests creation of nanotubes and nanowires for a nanostructure emitter is the best approach. The study shows that ideally, it is possible for a thermionic convertor to approach the Carnot efficiency. [21]

6. **Results and Comparison**

| Parameter                  | Thermoelectric | Thermionic | Photovoltaic |
|----------------------------|----------------|------------|--------------|
| **Temperature range**      | 200-850°C      | 600-2200°C | 30,000 to 100,000 lux (light) |
| **Laws**                   | Seeback effect | Richardson Equation | Photovoltaic principle |
| **Efficiency achieved**    | 6-8%           | 12-15%     | 15-22%       |
| **Applications where it is used** | Power plants, Automotive | Space power applications, Electric bulb, Cathode ray tube etc. | Domestic, Industrial, Power plants etc. |
| **Generation**             | 1.3 W/cm²      | 1.0-10 W/cm² | 1.4 W/cm²   |
| **Commonly used materials** | Bismuth telloride (Bi₂Te₃). | Tungsten, Rhenium, Molybdenum | Silicon, Cadmium telluride, etc. |
| **Limitations**            | ZT<3           | Space charge effect, Work Function | Depended on sunlight intensity |

**Table 2.** Comparison of direct energy converters.
7. Conclusion
The review explores enhanced battery management system and optimizations in regeneration system for hybrid electric vehicle. The waste heat analysis of different hybrid electric vehicles shown in Fig No.2 is important for considering the heat losses. Average 40-50% heat is lost to environment which can be recovered and reused. This needs a direct energy conversion because the amount of heat is not enough for conventional energy generation. It is evident from the literature that the current research in thermoelectric generator is limited by only 6-8% conversion efficiency with restricted ZT value of 2.5 approx [33]. This efficiency is not sufficient for hybrid electric vehicle performance optimization [31]. The thermionic energy conversion stands more efficient for waste heat recovery applications. Equation (1) shows, it is possible for thermionic energy converter to achieve Carnot efficiency as it is a non-contact type direct energy converter [35]. The comparative study in Table 2 is an outcome of the recent research works which are reviewed in this paper. It can be concluded that thermionic regeneration system has better opportunities in hybrid electric vehicle for improving the performance in terms of extension in drive range.

References
[1] Country wise petroleum consumption, US energy information administration, International energy statistics data. Retrieved from https://www.eia.gov/beta/international/data/browser/
[2] Global atmospheric CO2, Earth System Research Laboratory, Colorado. 22 April 2017.
[3] Claudio C, Federico M, Giulio B, Giuseppe D, Biagio C, Georgios F and Germana T 2017 Impact of Different Driving Cycles and Operating Conditions on CO2 Emissions and Energy Management Strategies of a Euro-6 Hybrid Electric Vehicle. Energies 2017, 10, 1590.
[4] Chokri M., Aymen F and Lassaad S 2014 Overview of Electric Vehicle Concept and Power Management Strategies. International conference of science and electrical technologies of Maghreb CISTEM 2014, Tunisia.
[5] Yinjiao X, Eden M, Kwok T and Michael P 2011 Battery Management Systems in Electric and Hybrid Vehicles. Energies, 4, 1840-1857.
[6] Languang Lu a, Xuebing Han a, Jianqu Li a, Jianfeng Hua b, Minggao Ouyang a 2012 A review on the key issues for lithium-ion battery management in electric vehicles. Journal of power sources, 226, 272-288.
[7] Joyce M, Miller J, Eric O'Shaughnessy, Eric Wood, and Evan Shapiro 2016 Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure Availability, and Vehicle Type. National Renewable Energy Laboratory, U.S. Department of Energy, Technical Report NREL/TP-6A20-64852.
[8] Thomas J, Shean H, Brian W and Paul C 2017 Fuel Consumption Sensitivity of Conventional and Hybrid Electric Light-Duty Gasoline Vehicles to Driving Style. SAE International.
[9] Emilia S, Theo H, Nikolce M, Pascal E and Maarten S 2015 Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles. IEEE Transactions on Vehicular Technology.
[10] Adam V, Ramachandran D, Gupta R and Antoine R 2012 Improving Hybrid Vehicle Fuel Efficiency Using Inverse Reinforcement Learning. Proceedings of the Twenty-Sixth AAAI Conference on Artificial Intelligence.
[11] Alan M, Nicholas J, Bobby R, Ellen J and William R 2010 Enhanced Plug-in Hybrid Electric Vehicles. IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply.
[12] Georgios F, Panayotis P and Zissis S 2008 Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles. Atmospheric Environment Volume 42, 18, 4023-4035.
[13] Hannan A, Azidin A, Mohamed A 2014 Hybrid electric vehicles and their challenges: A review. Renewable and Sustainable Energy Reviews, 29, 135-150.

[14] Johri, et al. 2017 US Patent No. US 9,637,109 B1. Washington, DC: U.S. Patent and Trademark Office.

[15] Warake K, Bahulikar S and Satpute N 2018 Review of Regenerative Braking in Electric Vehicles. International Journal of Engineering Science and Computing, 8, 18351-18353.

[16] Teresa D 2012 Intelligent Usage of Internal Combustion Engines in Hybrid Electric Vehicles.

[17] Jarman T, Jarman E and Khalil K 2013 Energy Analyses of Thermoelectric Renewable Energy Sources. Open Journal of Energy Efficiency, 2, 143-153.

[18] Orr B, Akbarzadeh A, Mochizuki M and Singh R 2015 A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes. Applied Thermal Engineering, 101, 409-495.

[19] Harold S 2007 Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle. US Department of Energy under MURI Program Energy Efficiency Renewable Energy (EERE).

[20] Humphrey T, O’Dwyer M and Shakouri A 2005 A further comparison of solid-state thermionic and thermoelectric refrigeration. 24th International Conference on Thermoelectrics, 196-199.

[21] Kamarul A, Abdul K, Thye J and Khairudin M 2016 Review on Thermionic Energy Converters. IEEE Transactions on electron devices, 63, 2231-224.

[22] David B, John R., Jeffrey G, Jochen M, Robin W, Alireza N and Robert N 2017 Thermionic energy Conversion in the Twenty-first Century: Advances and Opportunities for Space and Terrestrial Applications. Journal Frontiers in Mechanical Engineering, vol 3, article 13.

[23] Country wise carbon emissions from transport, U.S. department of commerce, N.E.S.R.L. ESRL global monitoring division—global greenhouse gas reference Network (26 may 2017). Retrieved from http://www.esrl.noaa.gov/gmd/ccgg/institu/

[24] Co2 emissions from transport (% of total fuel combustion) data (22 April 2017). Retrieved from http://data.worldbank.org/indicator/en.co2.tran.zs

[25] Rajat D, Shivanshu G, Russell H, Huddar N, Iyer B and Mangaleswaran R 2017 The future of mobility in India: Challenges & opportunities for the auto component industry. 57th annual conference organized by the Automotive Component Manufacturers Association of India (ACMA) by McKinsey & Company, Inc.

[26] Detlev M et al. 2016 Automotive revolution perspective towards 2030, Advanced Industries January 2016, McKinsey & Company.

[27] Rokadiya S and Bandivadekar A 2016 Hybrid and Electric Vehicles in India-Current Scenario and Market Incentives. International Council on Clean Transportation, 2016.

[28] Vidhi R and Shrivastava P 2018 A Review of Electric Vehicle Lifecycle Emissions and Policy Recommendations to Increase EV Penetration in India. Energies 2018, 11, 483.

[29] Reddy K, Aravindhan S and Mallick K 2017 Techno-Economic Investigation of Solar Powered Electric Auto-Rickshaw for a Sustainable Transport System. Energies 2017, 10, 754.

[30] Francis A., Sajjad F and Matt H 2012 Hybrid Electric Vehicles Challenges: Strategies for Advanced Engine Speed Control. IEEE International Electric Vehicle Conference.

[31] Huan-liang tsai and jium-ming lin., "Model building and simulation of thermoelectric module Using matlab/simulink,” Journal of Electronic Materials 39(9):2105-2111 (2009).

[32] F. S. Lo, p. S. Lu, b. Ragan-kelley, a. Minnich, t. H. Lee, m. C. Lin, and j. P. Verboncoeur., “Modelling a thermionic energy converter using finite-difference time-domain particle-in-cell simulations,” Physics of Plasmas 21, 023510 (2014).
[33] Meir, S., Stephanos, C., Geballe, T. H., and Mannhart, J. (2013). Highly-efficient thermoelectronic conversion of solar energy and heat into electric power. *J. Renew. Sustain. Energy* 5, 43127.

[34] Lee, J, Bargatin, I, Iwami, K, Littau, K, Vincent, M, Maboudian, R, et al., “Encapsulated Thermionic Energy Converter,” 493–496 (2012).

[35] McCarthy, T, Reifenberger, R and Fisher, T., “Thermionic and photo-excited electron emission for energy-conversion processes,” *Front. Energy Res.* 2:54 (2014).