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Research in vehicles with thermal energy recovery systems

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Abstract

This feasibility report presents results in the thermal energy recovery systems (TERS) investigation, and the possibility of introducing them to production vehicles as subsystems. This prospective new technology should reduce dependence on fossil fuels. One of the TERS systems' research objectives is to create a sustainable, electrical power source, suitable for the energy to be stored and later used in the electrical vehicle driving mode (EV)¹. It will also lower the impact on the environment by reducing fuel consumption through the application of automotive thermoelectric generators (ATEG) instead of classical alternators that convert mechanical energy to electrical. Instead of using part of the useful mechanical power, i.e. energy, we will be using wasted heat energy emitted in the environment. Investigation was carried out comprehensively by performing technical analysis, covering a wide variety of hybrid vehicles and systems. Finally, as an outcome, this report presents possible novel solutions to create sustainable hybrid vehicles with TERS systems.

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1. Introduction

Automotive manufacturers are coming under growing pressure from governments, environmental groups and society, to reduce environmental impact which automobiles and engines in general have on the community and planet. This is based on the various gases emissions and particularly high carbon dioxide levels released into the atmosphere. In addition to that, fossil fuels burning releases excessive heat into the environment. At the same time,

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society still places demands on vehicle manufacturers to retain the current attributes of performance, speed and durability, which engines and vehicles currently display. Following that, among other research streams, manufacturers and designers are conducting research and development programs, in the area of thermal energy recovery systems. Thermal electric generators (TEG) are used to recover the thermal waste energy from the engine exhaust system, cooling system, gearbox, clutch and differential to produce electrical power. Advancements were possible thanks to the rapid developments of thermal electric generators and Silicon / Silicon Carbide (SI/SIC) semiconductors technology. Motor generator units – heat (MGU-H)² are in the early stages of development. They also recover the thermal waste energy from the turbo exhaust gases. This research report discusses methodologies and technologies, which could be used, to extract the wasted thermal energy from the engine's combustion chamber, to create a sustainable TERS hybrid system.

Nomenclature

H_u	Lower heating value [J/kg]
M_f	Fuel mixture Mass [kg]
P_{TEC}	TEG predicted power at predicted efficiency [W]
Q_{in}	Rate of heat input [W]
Q_{max}	Maximum heat release
Q_{th}	Heat release [W]+ time + h Specific enthalpy [J/kg]
T_c	Heat engine minimum operating temperature [C]
T_h	Heat engine maximum operating temperature [K]
ZT_{TEG}	TEG figure of merit

1.1. Efficiency of hydrogen internal combustion engine combined with open steam Rankine cycle

The research was based on a hydrogen internal combustion engine, combined with the open steam Rankine cycle recovering water and waste heat³. The researchers found that when 1 kg of hydrogen mass is supplied to the engine, it produces approximately 9 kg of water, generated chemically by the combustion process. This is expected since the isotopic masses of Hydrogen, ¹H, and Oxygen, ¹⁶O, are 1.007825 and 15.994915 respectively with more than 99% of abundance in both cases. Having in mind water molecule formula, H_2O , this proportion was expected.

Water in the exhaust system⁴ is normally lost as waste through the exhaust pipe. Following that, the researchers' primary focus was to separate the water from the hydrogen internal combustion engine, through the exhaust system. Capturing the water provides the required working fluid for the TERS Rankine open steam cycle and the generation of electrical power that may be utilized to supply power to the battery, driving electrical devices or for other purposes. The thermal waste heat and water recovery system, based on the TERS - Rankine cycle, is made up of 5 main components: a *Water separator, Tank, Pump, Evaporator* and the *Expander*.

1.2. Recovering exhaust heat from internal combustion engines

Research was carried out looking at the thermal efficiency and heat extraction from the exhaust gases and engine coolant system⁵. The project objective was to recover heat from the exhaust gases after they leave catalytic converter. TEG mounted on the exhaust heat exchanger, converted the heat to electrical power, which was used to power an electrical motor, as a proof of concept.

1.3. Waste energy recovery study using Rankine cycle

Many studies were conducted on waste heat energy recovery that is used to power various systems⁶⁻⁹. Analysis was carried out on the waste heat from the hot exhaust of gas turbines, and internal combustion engines, to generate electricity through a Rankine power cycle. The Rankine cycle is predominately used in the electrical power production plants which convert heat to electricity using high pressure steam turbines.

1.4. Thermoelectric power generation system, for future hybrid vehicles, using hot exhaust gas

Research programs conducting studies on thermoelectric power generation systems for future hybrid vehicles are concentrated on new technologies and methods used to extract thermal heat energy¹⁰⁻¹². One of the research projects was focused on the development of new TEG unit¹³, using thermal heat transfer for creating working fluid. The TEG unit was mounted onto the exhaust pipe, with 10 angled copper heat pipes (Φ 20mm) directly placed into the exhaust pipe to transfer hot gases. Hot exhaust gases, of 200-300°C, travelled up the angled pipes to warm the heat sink, hot thermoelectric plate module and semiconductors.

1.5. Electricity generation from an exhaust heat recovery system utilising thermoelectric cells and heat pipes¹⁴.

Research was carried out looking into thermoelectric generator units mounted between a cooling air duct and a hot exhaust duct. The tests were conducted using a single cylinder engine as a heat source and a small electric motor mounted to the crankshaft. Electric motor was used to provide the air flow and cooling required for the TEG unit and air tubes. TEG works on a cross flow configuration, directing heat from one side to the other, through the heat pipes. The TEG cooling cycle is also configured in a cross flow arrangement through the cooling tubes. Heat flow and cooling flow, applied to both sides of the TEG unit, provide a junction point within the TEG unit for the generation of electrical power. Temperatures ranged between 198 to 38 degrees over the 8 cells, were rapidly declined, due the expanding gas and moisture in the exhaust.

1.6. TEG units and applications

TEG units are used in a variety of applications, ranging from low, medium and high temperature energy sources. In automotive industry we have combined TEG and Rankine cycle TERS collecting energy from exhausted gasses. TEGs are also found in solar panels, solar hot water systems, energy power stations, biomass powered stoves¹⁵ and solar pond¹⁶ systems with air turbine incorporated into a solar chimney. Many of these systems are combined together to enhance their efficiencies and power output. All of them operate by the same principles of heating up one side of the TEG unit and cooling the other side – Seebeck effect. This effect is known as direct conversion of temperature differences, ΔT , into the voltage, i.e. electromotive force E_{emf} as per formula given in equation (1):

$$E_{emf} = -S \Delta T \quad (1)$$

Proportionality constant S is Seebeck coefficient. Thermal heat sinks play important role in controlling the thermal heat flux, generated by the heat energy source. TEG thermal materials vary and depend on the temperature range. Bismuth telluride material is suitable for the range of 300 – 550K, Mercury-stainless steel thermosiphon for 525 – 850K and Potassium-nickel thermosiphon with silicon germanium for 850 – 1200K¹⁷.

1.7. TERS units and applications

The literature review has established that the Rankine cycle is the preferred method to recover thermal heat energy and convert it into electrical power. The three critical points to the Rankine cycle are high temperatures; high pressure and the extraction point where system engages the Rankine cycles working fluid and convert to electrical power. TEG systems, as another approach, can vary in there construction and applications. They are constructed with P and N type of silicon, Si , and silicon carbide SiC – semiconductors, as shown in Fig. 1a.

A sustainable thermal energy recovery system aims to bring together the Rankine cycle and TEG – SiC Semiconductors to extract the thermal heat energy from each of the internal combustion chambers, as reliable high temperature energy sources. The objective of the research is to engage the Rankine cycle working fluid at the maximum energy point, before the gases expand and cool in the combustion chamber and exhaust system. The TEG unit is positioned where it will receive the thermal heat flux from the combustion chamber maintained at operating temperature of around 600 degrees.

2. Power Source

The Rankine cycle converts low pressure fluid to high pressure through a compression process, where it applies heat to the fluid before releasing the high pressure through a turbine to a low pressure working fluid. It can be replicated in the internal combustion chamber using the intake, compression, power - ignition and exhaust cycles to create the required working fluid. This is used to capture the thermal waste energy at high temperatures, ranging from 500 – 900 degrees, in the combustion chamber, (Fig. 1b.), before they are lost through the exhaust valve. This will result in creating a lower temperature energy source for the TEG – SI/SIC semiconductors and MGU-H.

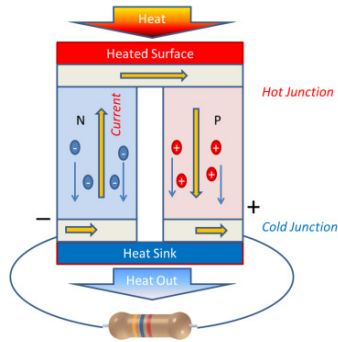


Fig. 1(a). Seebeck Effect

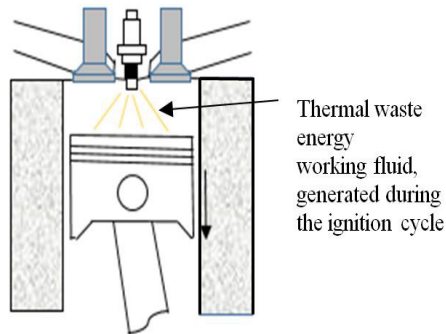


Fig. 1(b). Combustion chamber working used to convert heat into electrical power before it cools down in the exhaust manifold.

Air and fuel mixture conversion to thermal energy is given as following:

$$W_{\text{Thermal energy conversion}} = Q_{\text{max}} = Q_{\text{th}} = M_f H_u \quad [J] \quad (2)$$

From the equation (2) we can calculate the maximum heat energy W , generated from the air and fuel mixture. We are trying to recover some of that energy.

3. Power investigation

Capturing the high thermal heat energy directly from the engines combustion chamber is a critical process of extracting the maximum energy from the heated working fluid. It occurs at the peak of the compression and ignition heat cycle, before the fluid expands and leaves the combustion chamber. The expansion of the working fluid enables the moisture to dramatically reduce the temperature of the exhaust gases, creating a low heat energy source. On average, exhaust gas temperatures can range from 500 – 900 degrees, which is dependent on different automotive manufacturers and design requirements. Energy lost between the engine flywheel and the combustion chamber can vary between 4.8 – 9.6 kW. Table 1 displays the lowest figure of 5%. It is expected that efficient hybrid engines have minimal friction and torque losses. The overall system efficiency of combined organic Rankine cycle systems with TEG is increased¹⁸.

Calculation of system efficiency is given as:

$$W_{\text{TEG predicted}} = \left(1 - \frac{T_c}{T_h}\right) \dot{Q}_{in} \frac{(\sqrt{ZT+1}) - 1}{(\sqrt{ZT+1}) + \frac{T_c}{T_h}} \quad (3)$$

From the equation (3) we can see the thermal waste energy flow and cooler air flow, between each side of the semiconductors and what the operating efficiencies are.

Combustion chamber Total Power [kW]	TERS efficiencies	Recovered power from single cylinders [kW]	Total power for 4 cylinders [kW]
107.94	-5%	25.63	102.54
	-10%	24.28	97.14
	-15%	22.93	91.74
	-20%	21.58	86.35

4. Combustion chamber access

Accessing and extracting the thermal heat energy from the combustion chamber provides interesting research questions and challenges. The sustainable TERS system is conceptually designed without altering, or changing any of the engine's critical parameters, such as the camshafts, spark plugs, valves and cooling water jackets. An internal combustion chamber TEG unit is specifically designed to work around the critical dimensions and parameters. Another key element is to retain the serviceability and maintenance requirements. There are 12 key critical factors should be considered when placing TEG unit directly into the combustion chamber.

TERS application key issues are as following:

- 1) TEG capable of recovering 10-30 kW per cylinder,
- 2) Access to the combustion chamber,
- 3) Retaining compression ratio and volumetric efficiency,
- 4) TEG which uses platinum material,
- 5) Isolated TEG from the engine oil,
- 6) Strategically positioned TEG from camshafts and rockers,
- 7) Ventilated cooling system for TEG and ignition coils,
- 8) TEG screwed into combustion chamber,
- 9) TEG to accommodate the spark plug,
- 10) Access for the ignition coils,
- 11) TEG valve clearance and structural strength,
- 12) TEG - EMC compatibility.

TEG capable of recovering heat energy and converting it to electrical power, ranging between 10-30 kW per cylinder is critical to establishing a sustainable TERS system. The combined total power generated from all cylinders could reach over 200 kW of consistent electrical power in some circumstances such as with Porsche 918 and LaFerrari hybrid vehicles.

Access to the combustion chamber could be gained through a larger spark plug vertical axis hole, which is big enough to accommodate mounted TEG heat substrate and spark plug. A caution point is not to make the hole to big which will interfere with the valves and possible stress fractures, generated from heat and the consistent opening and closing the valves under high spring tension.

Retaining the compression ratio and volumetric efficiency of the combustion chamber dimensions is critical to maximise the volume energy of the originally engine design parameters. A change to the combustion chamber profile, by the means of a TEG substrate protruding into the combustion chamber, will reduce the capacity of the chamber volumetric efficiency and reduce the compression ratio. A TEG substrate that has a counter sunk contact face will create a higher compression ratio and will require a supercharger to compress more fuel into the combustion chamber, or long fuel injection pulses, to allow more fuel into the combustion chamber, which will create much higher fuel consumption.

TEG which uses Platinum material on the TEG substrate face to recover the thermal heat energy from the combustion chamber and convert to electrical power. The use of platinum for the TEG substrate is important because it will not oxidise and has high energy conductivity. This material has a very high melting point of 2041.0, Kelvin¹⁹, which makes it well suited for the high temperatures in the combustion chamber.

TEG needs to be isolated from the engine oil swishing around in the cylinder head that could affect the performance, durability and life cycle of the TEG unit. If the TEG unit is not sealed correctly and is exposed to oil, which could cover the TEG, it will potentially short the electronics within the unit. It will also leak into the combustion chamber covering the TEG substrate heat contact face with an oil film, affecting the heat conductivity and the fuel burning efficiency of the combustion chamber. To prevent this, the cylinder head requires a cylindrical extrusion that is cast into the cylinder head during the manufacturing phase, to isolate the TEG unit from the oil swishing around in the cylinder head. The cylindrical extrusion also needs to be larger enough to fit the TEG unit into. The isolation in the cylinder head extrusion will create higher operating temperatures of the TEG unit, so it will require a cooling system to ensure it operates efficiently and supplies enough air flow and cooling for the semiconductors.

Strategically well positioned TEG that does not interfere with the camshafts rockers and is located directly in line with the traditional location of the spark plug. It will also need to accommodate for the cylinder head TEG extrusion which is based around the spark plug vertical axis threaded hole.

Well ventilated cooling system should provide adequate flow to the combustion chamber TEG unit, semiconductors and the ignition coils, which are capitulated in the cylinder head cylindrical extrusion - spark plug access hole. Obtaining maximum cooling efficiency can be achieved by constructing a cross flow design that would adequately dissipate the heat which is channelled up from the cylinder head cylindrical extrusion and dissipate it out of the cooling exit.

TEG that can be screwed into the cylinder head would need to seal the combustion chamber and also prevent compressed fuel escaping from the chamber, which are hazards and will cause fires. It also needs to prevent oil from entering into the combustion chamber, the loose of compression, creating poor engine running and excessive wear to the engine. To seal the TEG unit, it is recommended that the unit be tightened to a prescribed torque, similar to that of the traditional spark plug, which will enable the TEG sealing taper or 90 degrees sealing seat with washer to seal the combustion chamber.

TEG that accommodates the spark plug is a different approach from the conventional means of screwing a spark plug into the combustion chamber. Combining the TEG substrate and spark plug together overcomes the physical limitations of fitting a TEG into the chamber. It will also take into account the intake and exhaust manifolds blocking access to the heat energy source and the change to the volumetric efficiency within the combustion chamber. The TEG unit is based around a cylindrical design that is screwed into an oversized spark plug hole with the substrate centre hollowed out, to allow for a spark plug to be screwed and torqued into the base of the substrate, with the electrode protruding through the bottom. The advantage is the direct access to the thermal heat energy source of the combustion chamber, ranging between 500 – 900 degrees and ignition of the air and fuel mixture. The temperatures can vary, depending on different engine manufacturers and designs. Exhaust valve temperatures can range between 700 to 900 degrees, for mild steel and stainless steel.

Access for the ignition coils and clearance needs to be considered when designing the TEG unit, to enable the ignition coil pack and stork to fit onto the spark plug in the correct position. It should also be easily mounted to the cylinder head cylindrical extrusion with sufficient clearance to enable the heat generated from the spark plug and TEG to rise and escape for the cooling process.

TEG which does not interfere with the operation of the valves, or compromise the structural strength of the combustion chamber and valves seats: The TEG substrate must not protrude into the combustion chamber and should match its profile. Sufficient clearance will be required around the valve seats, so they do not crack, or deform from the heat and the frequent high application cycle of closing the valves, which are under high spring tension. To achieve this from a TEG design prospective, may require the TEG substrate thermal heat face to be designed in a four pointed star configuration around the shape of the valve seats, increasing the thermal energy recovery surface area. Due to the shape of the thermal face surface area, it will require a mounting design, from the top of the engine that seals the combustion chamber. Predominately this may be required in some cases for tightly arranged multi valve engines. Dual valve engines will have a significant surface area around the spark plug hole for a large thermal surface area. The enlarged spark plug hole diameter needs to be an appropriate size that will not interfere and create distortion and cracking of the valve seat. The cooling of the cylinder head must not be compromised.

TEG which is Electro Magnetic Compatibility (EMC) compliant, does not receive interference from the spark plug or ignition coils - directly mounted to the TEG unit. This is critical to the efficiency and operation of the TEG unit to accurately measure the thermal heat energy in the combustion chamber and block the electromagnetic pulse waves that are generated from the spark plug and ignition coils. A possible way to overcome the electromagnetic pulse waves is to insulate the TEG unit and deflect waves from the spark plug and coils.

5. Prototype Design

Internal combustion chamber TEG unit has been specifically planned to work around the critical dimensions and parameters, while still retain the serviceability and maintenance requirements. The system works on two well established principles of the heat transfer and thermo electric generation. Placing the unit directly into the combustion chamber will expose the TEG heat substrate to temperatures ranging from 500 – 900 degrees. It will also retain the original profile of the combustion chamber and volumetric efficiency. The TEG heat substrate, (displayed in Fig. 3. & 4.) transfers the heat up to the thermoelectric elements known as semiconductors *P* and *N* type. At that point the thermal heat mixes with the cooling system, to generate electrical power at the heat and cooling junction point. The collected electrical power from the SI/SIC semiconductors is sent to the voltage-boosting converter. The SI/SIC semiconductors have been placed in the cylindrical TEG unit, as an array configuration to accommodate the spark plug. The central location of the spark plug is tightened directly into the heat absorbing substrate and exposure the combustion chamber. The unit is designed in the form of cylindrical shape to maximize the thermal efficiency of the thermal corn element in the TEG unit that receives the heat transfer directly from the internal combustion chamber. Experiments, prototype building and extensive testing will be carried out in RMIT University Green Lab. Engine dynamometer testing and validation will be conducted on a modified RMIT – FSAE racing car as shown in the Fig.2.



Figure 2: RMIT - SAMME designed FSAE racing car that will be used for new TERS technology testing.

Novel combustion chamber TEG design is shown in Fig. 3(a), while the basic combustion chamber model is given in the Fig. 3(b).

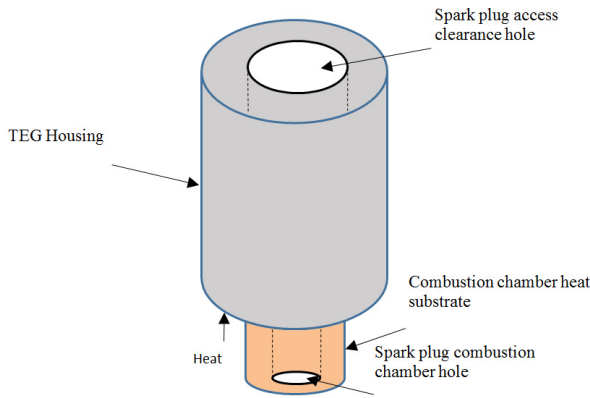


Fig. 3(a). Design of the combustion chamber TEG unit.

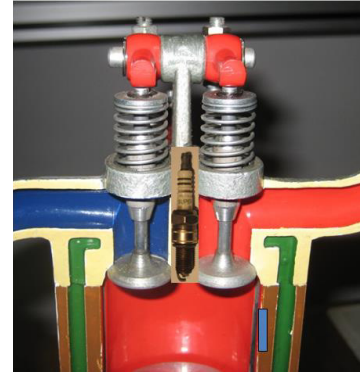


Fig. 3(b). A combustion chamber basic model

More details on combustion chamber TEG design and locations are shown in the Fig. 4.

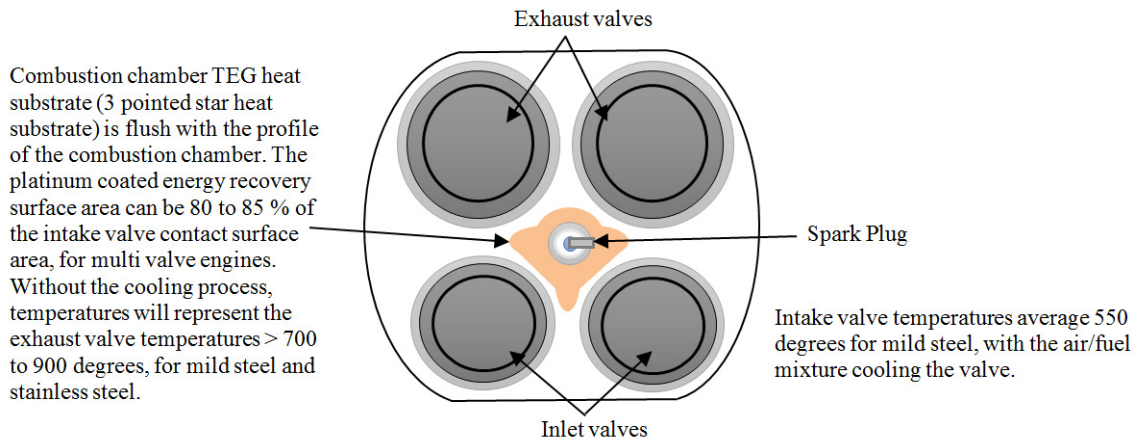


Fig. 4. The orientation of the combustion chamber TEG heat substrate with the spark plug mounted centrally within the heat substrate to maximise thermal heat transfer and efficiency. The TEG heat substrate design can also be configured as a 4 pointed star style to increase the heat substrate thermal surface area and to accommodate for the valves.

6. Sustainable TERS hybrid system modes

As already discussed, design of a sustainable electrical TERS will reduce the load requirements on the engine and the burning of fossil fuels. Retaining performances of the engine through the TERS system will provide alternative fuels such as ethanol *E85* and *E100* the opportunity to be used and counter balance ethanol's lower fuel economy range when compared to petrol. Ethanol has a lower energy density of *21.31 MJ/l* when compared to petrol energy density of *32.0 MJ/l*.

The advantage of creating a sustainable TERS hybrid vehicle, using the consistent high energy source in the combustion chamber, enables the driver to choose which mode they would like to drive in to suit the conditions. The standard and deluxe default modes, in which hybrid vehicle could operate, will have the TERS system that will supply energy to the battery system. It will deliver power to the electrical motor and at the same time reduce fuel

demands on the combustion engine. The electrical vehicle (EV) mode, powered by the energy from the thermal energy recovery system will enable travel around cities like other electrical hybrid vehicles. The TERS system will also enable the vehicle to travel on highways and freeways in the EV mode, covering large distances. The TERS system briefly switches on to engine idle speed, generating electrical power and recharging the lithium-ion batteries, while still remaining in the EV mode.

The TERS system can also operate in a simplified version, using the TERS to solely power the hybrid system, removing the lithium-ion storage batteries. This configuration could suit high performance sports cars, racing cars and the creation of sustainable hybrid motor bikes. There are already investigations in combined TEG and Dual-loop Organic Rankine cycle (DORC).

Electrical power distribution with thermal energy recovery system (TERS) is shown in the Figure 5.

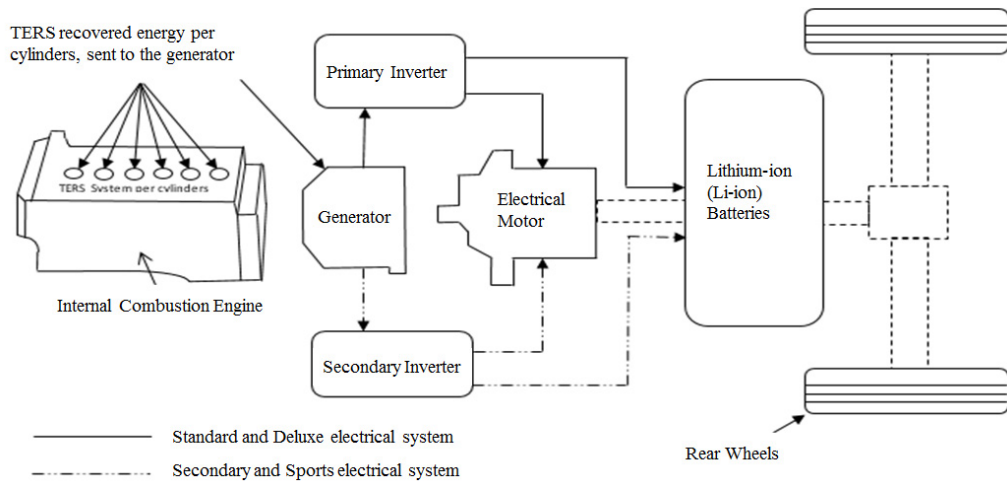


Figure 5 Standard and deluxe primer system, and the secondary sports modes. Components for the EV driving mode as shown as well.

7. Conclusions

After conducting feasibility studies and technical analysis on the thermal energy recovery systems' research and development, we have come up with the idea to use TEG heat extractor directly mounted into the engines internal combustion chamber thermal contact surface area. Extraction of thermal heat energy from the internal combustion chamber is a novel approach not explored yet in the scientific community. This is based on the idea of recovering and extracting energy from the high temperature source ranging from 500 – 900 degrees, in the combustion chamber, and converting it to electrical power. Conversion from heat to electrical power is carried out using thermoelectric generators. The engine internal combustion chamber provides a sustainable and reliable heat energy source. There is a large number of research questions, related to the operating ranges of TEG devices and their reliability in the extreme cases, i.e. environments. Based on this and future investigations, a hybrid vehicle with TERS will be constructed. Comprehensive investigation of the TEG technology constraints, new TEG design and development, together with the simulations and testing are our current and future research objectives.

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