A Review on Energy Harvesting Techniques and Ways to Optimise the Energy Regeneration from Waste Heat

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Abstract

Due to energy crisis as well as environmental pollution issues, it is necessity for the establishment of alternatives energy harvester system in reducing the dependency of the primary resources such as oil and coal. This paper will firstly review the basic concept of the thermoelectric (TE) which able to harvest waste heat energy and convert it to electrical energy and vice versa. The recent applications of the thermoelectric generator (TEG) at various areas in term of its design structure and performance will also be reviewed. To optimise the TEG performance, some important parameters to be considered are the temperature difference between hot and cold side, the figure of merit (ZT) of the TEG and the power management in which these factors are significantly affecting the output power and the conversion efficiency of the TEG system. From this review, it is concluded that proper design of the TEG system is required to improve the energy conversion efficiency. Thus, for future improvements, an optimal energy harvester system has been proposed at the last section of this paper.

Keywords: Greenhouse, Energy Harvester, Thermoelectric Generator, Power Management Circuit.

1.0 Introduction

Energy is very important in our daily life which is not only needed for the growth and movement but it also covers all aspects of human activities. It may be difficult to move from one place to other places without using vehicle and we may not be able to cook if we ran out of energies, e.g. electrical energy from natural gas, coal, petrol and diesel. The road traffic control may also be in problem due to the non-functioning traffic lights or street lights. Those

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who are working in the high rise building will also face difficulties of using the stairs as the elevator fails to operate due to the lack of electricity.

Moreover, energy is needed especially for the development countries in which the more rapid development it takes, the more energy is required to meet that development. However, the most serious challenge is to reduce the greenhouse emission due to the increasing of energy usage and the exploration of many resources [1]. The greenhouse gases which emitted by various energy sources are shown in Table 1 [2]. Therefore, new alternative technologies need to be developed to sustain the energy which able to reduce the dependency on it.

Table 1. List of energy sources [2]

Energy Sources	Green-house gas emission		
	CO_2	SO_2	NO_x
	g/kWh	g/kWh	g/kWh
Coal (best practice)	955	11.8	4.3
Coal (NO_x) and FGD	987	1.5	2.9
Oil (best practice)	818	14.2	4.0
Natural gas (CCGT)	430	–	0.5
Diesel	772	1.6	12.3
Small hydro	9	0.03	0.07
Large hydro	3.6–11.6	0.009–0.024	0.003–0.006
Wind	7–9	0.02–0.09	0.02–0.06
Solar photovoltaic	98–167	0.2–0.34	0.18–0.30
Solar thermal electric	26–38	0.13–0.27	0.06–0.13
Energy crops – current practice	17–27	0.07–0.16	1.1–2.5
(likely to improve to)	(15–18)	(0.06–0.08)	(0.35–0.51)
Geothermal	7–9	0.02	0.28

Power harvester is a device that converts a source of energy into another form of useful energy. There are four types of energy source have been highlighted in [3] which are wind, heat, solar, and hydro. Each type of energy had been reviewed in term of their source of availability, energy conversion efficiency and feasibility on micro-scale application as shown in Table 2.

Heat energy has been determined as the best availability source because of its permanent availability such as temperature from human body skin, heat dissipates from machine and many more. Even though, heat energy had been identified as the lowest energy conversion efficiency as compared to others but it is significantly more reliable.

Table 2. Energy source comparison [3]

Types	Source Availability	Energy Conversion Efficiency	Feasibility on Micro-scale Application
Wind	Depend on weather	Varies depending on source	Not suitable as wind speed is not constant
Heat	Always available e.g. on human body temperature	Low	Considerable with power management circuit under specific temperature range
Solar	Maximum six hours peak irradiance daily	Maximum during peak irradiance	Considerable with charge controller
Hydro	Available when there is high pressure water source	Conversion depending on water pressure	Considerable only with specific flow rate of water sources

2.0 Working Principle of Thermoelectric

In order to overcome the problems mentioned in Section 1.0, thermoelectric (TE) is one of power harvester device that could be implemented as part of solutions. It is a solid-state device that converts heat energy into electrical energy or vice versa and commonly used among people because of its few advantages that defined by Young in [4] such as no greenhouse gases required, silent operation, faster operation, light weight material, no chemical reaction and no movement components of the system.

As described in [5], TE is classified by two working principles that are Seebeck effect which is mainly for power generation (Thermoelectric Generator-TEG) while Peltier effect is mainly for refrigeration (Thermoelectric Cooler-TEC). Additionally, TE also consists of three types of material made from that are semiconductors, ceramics and polymers. Among of them, semiconductor is determined to have large Seebeck coefficient that can perform well and reliable for many years when it is operating at or near ambient temperature.

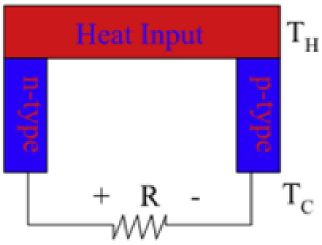

Figure 1. The Seebeck effect [5]

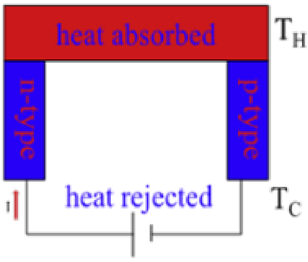

Figure 2. The Peltier effect [5]

The Seebeck effect is the phenomenon when a temperature difference between two dissimilar conducting materials produces a voltage difference between the two substances as shown in Figure 1. The maximum efficiency for TEG (η_{max}) can be described by the following equation (1):

$$\eta_{max} = \frac{TH-TC}{TH} \cdot \frac{\sqrt{(1+ZT)}-1}{\sqrt{(1+ZT)}+TC/TH} \quad (1)$$

Where

TH = Hot side temperature
TC = Cold side temperature
ZT = Figure of merit

The Peltier effect is inverse to the Seebeck effect in which a temperature difference created by applying a voltage between two dissimilar conducting materials that connected as shown in Figure 2. The maximum coefficient of the performance (COP) for TEC can be described by the following equation (2):

$$COP_{max} = \frac{TC}{TH-TC} \cdot \frac{\sqrt{(1+ZT)}-TC/TH}{\sqrt{(1+ZT)}+1} \quad (2)$$

Where

TH = Hot side temperature
TC = Cold side temperature
ZT = Figure of merit

TEG module basically consists of a large number of thermocouples connected electrically in series to form a module which will be discussed further. Heat from a target sources is absorbed to the surface of the module (hot side) and rejected at a lower temperature from the opposite surface (cold side).

According to Meng in [6], the performance of the TEG is not only dependents on its internal structure but the external irreversibility that may occur between device and heat transfer process should also be considered. Some features have been identified such as the effect of external heat transfer, figure of merit of the TEG and the air gap of the module within heat transfer.

Materials of both p- and n-type in thermoelectric module should have high figure of merit (ZT) [7] to have highly efficient TEGas described in equation (3):

$$ZT = \frac{\alpha^2}{k} \cdot \sigma T \tag{3}$$

Where

α = seebeck coefficient
σ = electrical conductivity
T = temperature
k = thermal conductivity

The properties of the TEG as mentioned by Elsheikh in [8] such as Seebeck coefficient, thermal conductivity and electrical resistivity need to be considered for making any improvement to increase the efficiency of TEG. The characteristic of the available TEG materials had been compiled in [9] as shown in Table 3.

Table 3. The characteristic of the available TEG materials [9]

Temperature (°C)	Type	TEG material	ZT (maximum)
< 150	p	Bi_2Te_3	0.8
	n	Bi_2Te_3	0.8
150–500	p	Zn_4Sb_3	–
	p, n	PbTe	0.7, 0.8
	p	TeAgGeSb (TAGS)	1.2
500–700	P	$CeFe_4Sb_{12}$	1.1
	n	$CoSb_3$	0.8
700–900	p, n	SiGe	0.6-1.0
	p	LaTe	1.4

TEG will deliver the maximum Power output (Volts x Amps) when the load resistance equals the TEG internal resistance [10]. This is called load matching or impedance matching which the "TEG resistance" chart shown in Figure 3 is used to determine the TEG internal resistance. The values of both the hot and cold side temperatures need to be added and divided by two to get the average temperature. It is important to keep the load resistance higher than the TEG resistance rather than lower. The general dimension of the TEG had been specified as shown in Figure 4 which describes different specifications summarized in Table 4.

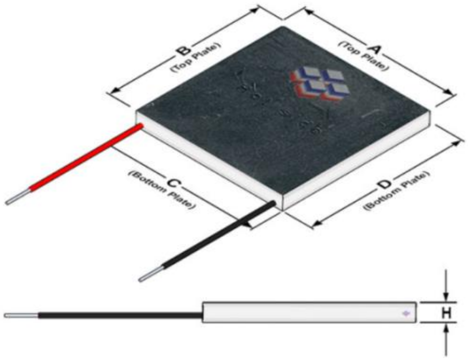

Figure 4. The general dimension of the TEG [10]

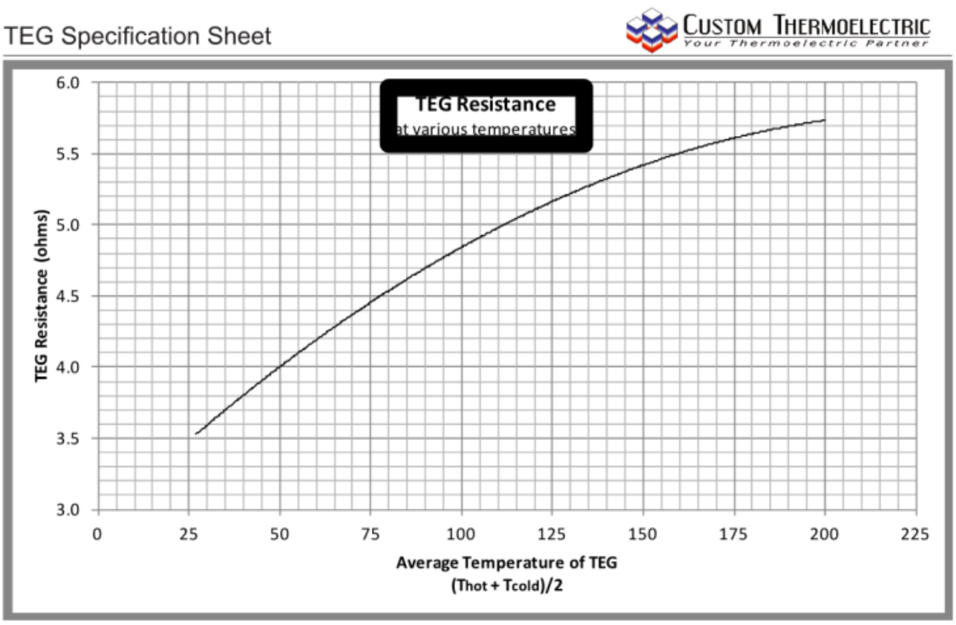

Figure 3. TEG resistance chart [10]

Table 4. Line with different specification for TEGs [9]

	Thermal & Electrical Specifications T=300°C (Hot side) T=30°C (Cold side)					Dimensions mm[inches]				
PART NUMBER	P (Watts)	I (Amps)	V (Volts)	Tmax (°C)	ACR (Ohms)	A	B	C	D	H
1261G-7L31-04CL	5.19	0.98	5.3	320	3.5	30.0 [1.181]	30.0 [1.181]	30.0 [1.181]	30.0 [1.181]	3.70 [0.146]
1261G-7L31-04CQ	7.5	1.56	4.8	320	1.7	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	3.40 [0.134]
1261G-7L31-05CQ	9.9	2.47	4	320	0.9	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	3.40 [0.134]
1261G-7L31-10CX1	16.2	3.68	4.39	320	0.65	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	4.40 [0.173]
1261G-7L31-24CX1	19.1	4.9	3.9	320	0.38	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	5.00 [0.197]
1991G-7L31-12CQ	10	1.8	5.6	320	1.75	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	40.0 [1.575]	3.40 [0.134]
2411G-7L31-10CX1	17.6	2	8.8	320	2.4	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	4.45 [0.175]
2411G-7L31-15CX1	21.6	3	7.2	320	1.75	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	56.0 [2.205]	4.45 [0.175]

3.0 TEG Application Areas

The improvement of the TEG system efficiency is much dependent on the temperature difference occurs between hot and cold sides of the TEG module which is determined by heat sources and the cooling method. Therefore, some previous designs about the performance of hot side and cold side of the TEG regarding to their sources have been compiled here for reference.

3.1 Application of TEG at car exhaust

Meng in [11] had studied on the TEG system that applied in automobile where the heat waste dissipates from the exhaust has been harvested. The experiment is conducted by making a model as shown in Figure 5 which consists of exhaust pipe, TEG module and water cooling heat sink. In the end, the author focused on testing the performance of TEG system in term of its conversion efficiency and output power that can improve fuel consumption efficiently.

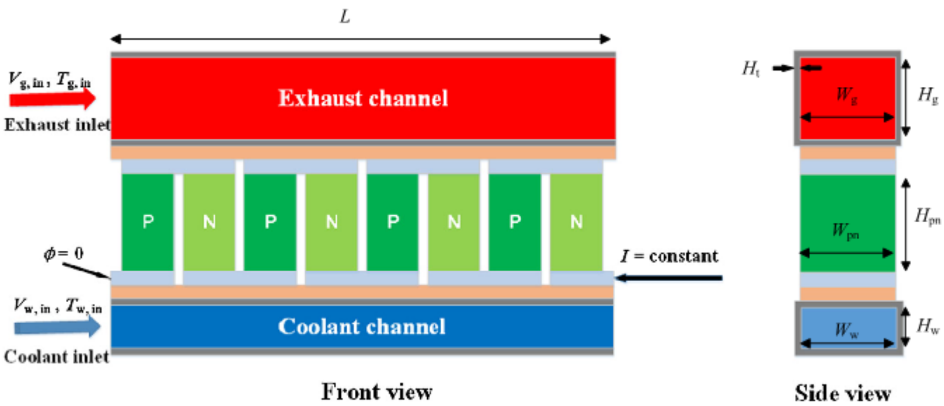

Figure 5. Energy harvesting from car exhaust [11]

3.2 Application of TEG at roof top

Lertsatitthanakorn in [12] had investigated the TEG system using direct solar as source of the heat and assisted by flat-plate reflection to capture more heat at hot side. The cold side was directly attached by copper heat sink that integrated with heat pump system to release the heat from the heat sink. A schematic diagram of the TEG system was shown in Figure 6. As a result, the TEG system was improved by using the reflector which the optimal position of the reflectors has been determined being better to give greater output power and conversion efficiency.

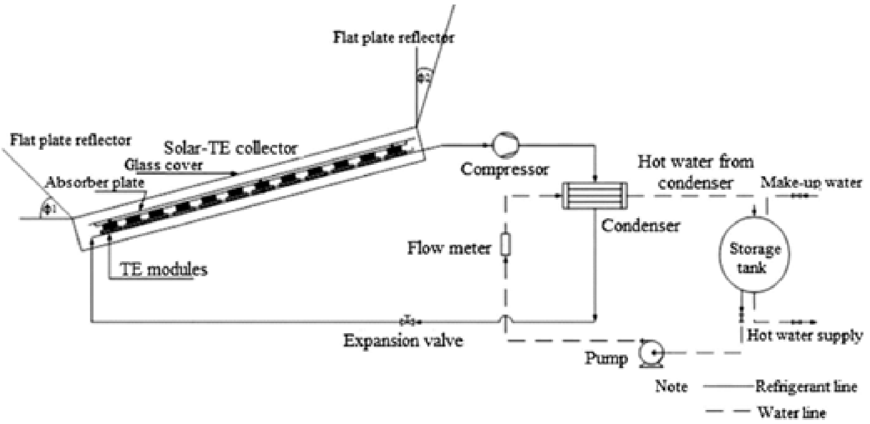

Figure 6. The schematic diagram of the TEG system for application at roof top [12]

3.3 Application of TEG at air conditioner

Yildiz in [13] has studied the performance of TEG system through an air conditioner condenser by fabricating a holder and clamper. Both holder and clamper are not only to fix the TEG module but it is made from copper to absorb more heat and transfer to the TEG surface to get higher gradient temperature. The schematic diagram of the experimental TEG system setup is shown in Figure 7. The maximum power output and the efficiency of the power system had been revealed for reference in future studies.

Figure 7. The schematic diagram of the experimental TEG system [13]

3.4 Application of TEG at computer microprocessor

Zhou in [14], had investigated the waste heat in a between microprocessor die surface and environment. The measurement has been made on Pentium III processor which running at 1GHz under varying workload. The schematic diagram of TEG system has been setup as shown in Figure 8 (side view) and Figure 9 (top view). The experiments were carried out for four different positioning of TEG module to measure the temperature different between top and bottom layer to determine the highest output power. The hot side has attached to the spreader to absorb heat from PCB while the other side is cooled by heat sink. The electrical energy generated from this waste heat energy then can be used to operate the other components in a system.

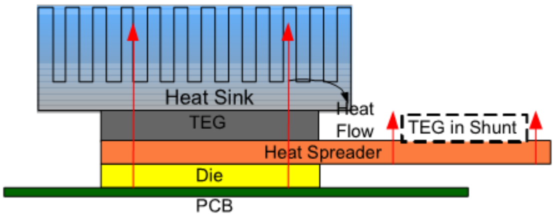

Figure 8. The schematic diagram of TEG system [14]

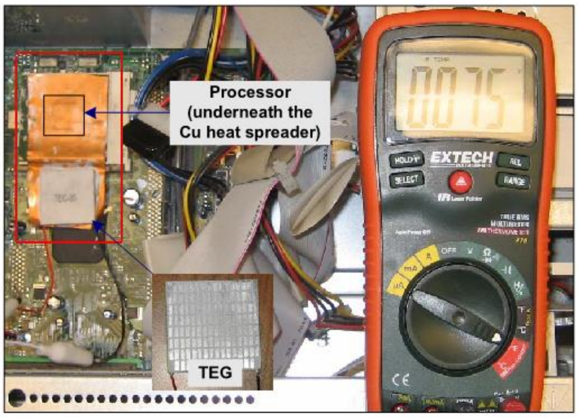

Figure 9. The system setup of TEG system [14]

3.5 Application TEG at car radiator

Kim in [15], had investigated the feasibility of a system heat by fabricated the TEG system to convert heat from the engine coolant of a car to electrical energy while the radiator air cooling fan was switched off. The prototype of the system was shown in Figure 10 and Figure 11 which consists of two major parts that are hot side block and cold side block have a sandwich structure. According to the measured temperature occurred, the output power and TEG efficiency has been revealed.

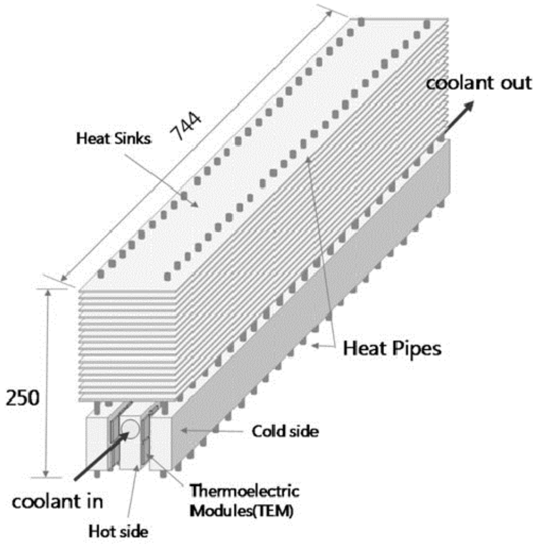

Figure 10. The prototype of TEG system for application at car radiator [15]

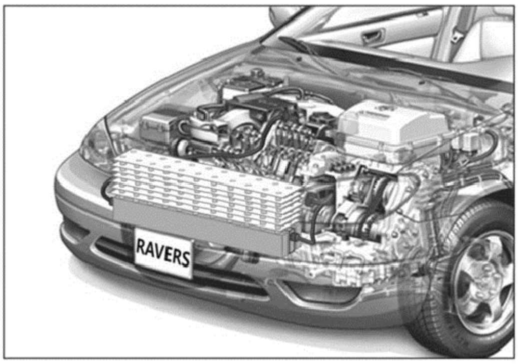

Figure 11. Application of TEG at car radiator [15]

3.6 Application TEG at cook stove

Mal in [16], has developed a TEG system integrated with a double chambered forced draft cook stove to generate power to run DC brushless fan of 5V, 0.3A. The heat input to the TEG is inside the cook stove and the temperature achieved was 250°C while the cold side which had built up with heat sink cooled by the fan as well and the temperature about 25°C. The schematic diagram of the experimental setup was shown in Figure 12.

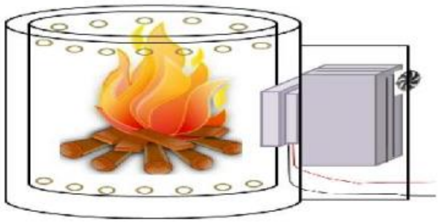

Figure 12. The schematic diagram for application TEG at cook stove [16]

3.7 Application TEG at electric heater

Usman in [17] had studied the efficiency of TEG system by enhancing a thick graphene layer placed on the cold side of the TEG module to provide effective heat dissipation in order to increase the temperature gradient across the TEG module. The TEG module has been installed at the electric heater to harvest the waste heat occurred. The maximum efficiency of the TEG system was improved by 25.45% compared to the TEG module without graphene layer. The schematic of TEG module and the experiment setup of TEG system were shown in Figure 13, Figure 14 and Figure 15 respectively.

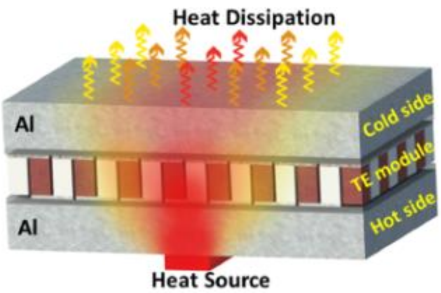

Figure 13. TEG system without grapheme [17]

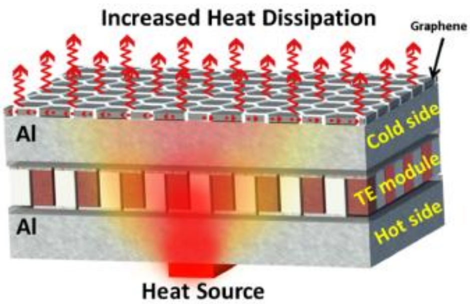

Figure 14. TEG system with grapheme [17]

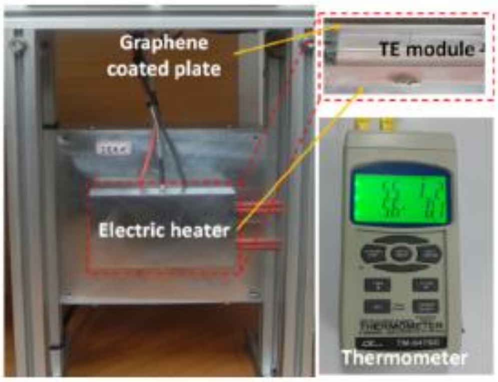

Figure 15. Application TEG at electric heater [17]

It is a crucial part to come out with an effective design structure of TEG system either providing hot side to absorb more heat or cold side to release more heat as per Table 5 due to some limitation on feasibility of the TEG module and the measurement capacity of heat.

Table 5. Comparison of TEG system design

Application Area	Heat Source	TEG System Design	
		Hot side	Cold side
Car	hot exhaust	hot air channel	water coolant channel + aluminium heat sink
Roof top	hot solar	direct solar and reflector	water coolant channel + copper heat sink
Air conditioner	hot condenser	copper clamper and holder	free air
Computer	hot microprocessor	direct contact and heat spreader	aluminium heat sink + free air
Car	hot radiator	hot coolant channel	aluminium heat sink + free air
Cook stove	hot cover	confine area	aluminium heat sink + fan
Electric heater	heating element	direct contact	graphene layer

4.0 Power Management Circuit

One of the challenges behind TEG is that the power generated is low and unstable so that it needs proper power management circuit before it is supplied to the load [18]. In order to make use of the thermoelectric generated power in applications requiring a higher voltage, a DC-DC converter that can handle low input voltage is needed [19].

The DC-DC converter can provide more stable power output thereby improving the overall efficiency of TEG system [20]. Generally, a DC-DC converter is an electronic circuit or electromechanical device that converts a source of direct current (DC) from one voltage level to another. Typically, DC-DC converter involves the storage of electrical energy into components such as capacitors and inductors, and the release of energy to loads.

There are four types of DC-DC converter are generally used in power electronic field to improve the voltage range which had been reviewed their characteristics and the schematic diagram was shown in Figure 16, Figure 17, Figure 18 and Figure 19 accordingly.

4.1 Booster converter

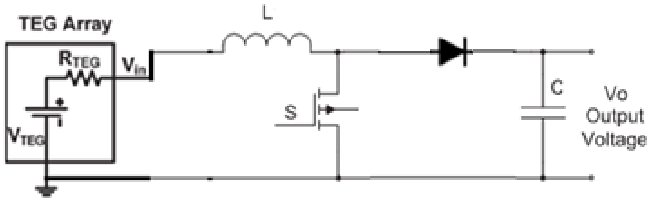

Figure 16. The schematic diagram of boost converter [21]

Carlson in [21] had performed an experimental using boost converter which operate the input voltage of the TEG ranging from 20mV to 250mV to supply 1V regulated output.

4.2 Buck boost converter

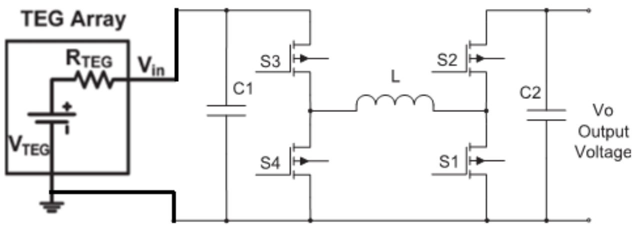

Figure 17. The schematic diagram of buck boost converter [22]

Win in **[22]** had reported that low power of TEG can be increased by using buck boost converter which the input voltage is 500mV to get 2.38V regulated output.

4.3 Sepic converter

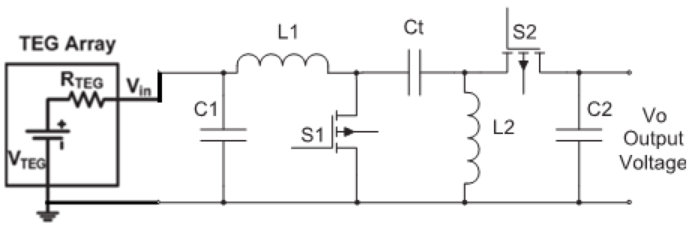

Figure 18. The schematic diagram of sepic converter [23]

Kinsella in [23] had involved in an experimental which need to deliver and store small amount of electricity by using sepic converter. According to the result the output voltage from sepic converter is 3.3V which get the input voltage from TEG is 2V.

4.4 CUK converter

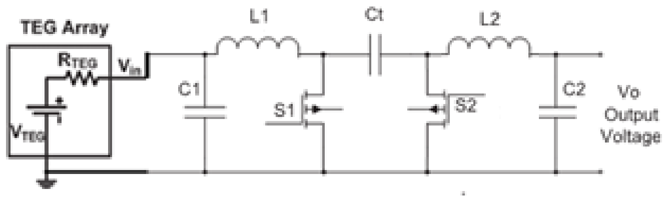

Figure 19. The schematic diagram of CUK converter [24]

Shameer in [24] had reported that by using CUK converter with 2V input of TEG system then had been amplified to 12V output.

The DC-DC converters are popular because they provide efficient power conversion. The less efficient converter will constantly require more input power to maintain the same output as the alternative device. Therefore, it is sensible to aim for the most efficient voltage converter for the application. The comparison of the operation characteristic of four converters had been made as shown in Table 6 [25]

Table 6. Operation characteristic of converters [25]

CHARACTERISTIC	BOOST	BUCK BOOST	SEPIC	CUK
Inductor Position	Good	Bad	Good	Good
Input-Output isolation	Difficult	Easy	Easy	Easy
Output Voltage Vo	> Vin max	Any	Any	Any
Start-up Capability	no, auxiliar	Inherent	Inherent	Inherent
Over Current Control	no	yes	yes	yes
Switch Voltage	Vo	Vo + Vin max	Vo + Vin max	Vo + Vin max

5.0 Conclusion and Future Work

Recently, the development of thermoelectric (TE) technology most likely can contribute to the global solution for renewal energy. TE technology is an alternative choice to convert waste heat energy into electricity .This paper mainly focuses on review of thermoelectric generator (TEG) technologies in term of its principle, application and power management system. There are several type of TEG material and its characteristic had been reviewed here.

The performance of the TEG is determined by the figure of merit (ZT) which is dependent on three physical properties that are electrical resistivity, Seeback coefficient and thermal conductivity. However, the feasibility and efficiency are some limitations of TEG technology.

TEG technology can be applied in many area based on research review [10] to [16]. The temperature plays a significant role for TEG application whereas the TEG output power increases proportional to temperature difference between the hot and cold sides. Different techniques had been structured in the TEG system either providing hot side to absorb more heat or cold side to release more heat in order to maximize the performance of TEG. In particular, to improve the performance of the overall TEG system, the implementation of the power management such as DC to DC converter should be highly considered. It is necessary to adopt this converter in the TEG system to provide more stable power output as well as to improve its efficiency. TEG technologies have bright future for many more various applications in industry or domestic usage if further advancements of the system design are carried out to improve its efficiency. Therefore, the future work in this area aims to develop an optimal energy harvester system of waste heat from household appliances e.g. air conditioners, heaters, refrigerators etc. that shall harvest high output power so it could somehow can be reused back to minimize the electricity usage of the applied device.

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