2.1. Introduction

Almost every country is increasing the share of renewable energy in their total energy budget owing to the issues of global warming. As a result, renewable energy from solar, wind, small hydro and biomass are being harnessed extensively over the last decade. Another alternative way of harnessing energy and its subsequent conversion is through waste heat recovery. Waste heat available at varying temperature ranges (low: 0-120ºC, medium: 120-650ºC, and high: >650ºC) can be utilized in the production of electricity, mechanical work and process heating. Thermoelectric generator (TEG) is gaining importance as a waste heat recovery technology for its inherent features of low noise, less maintenance with no moving parts. Operating in the principle of Seebeck effect, TEG can produce electric power with any heat source available. Literatures are available reporting the potential of TEG as an alternative technology for low and high power generation [1-3].

Soon, an increase in fuel prices will demand for an alternative source of power generation. TEG for its longer life (time of operation: 100000h) and being environment friendly, the odds will be in favour of TEG [1, 4].

Since the discovery of the Seebeck effect, researchers have been working on the conversion of heat into electricity using TE elements. Maria Theresa Telkes made the first TEG in 1947 based on Solar thermal. Application of TEG is also seen for space from 1970 through 1990, such as Radioisotope Thermoelectric generator (RTG) in various space exploration missions by NASA viz. Apollo, Pioneer, Galileo, Viking, and Voyager [5]. However, from the period 1990-present, applications of TEG to recover exhaust heat from IC engine-driven vehicles, biomass fired cook stoves and in integration with other renewable energy technologies such as solar photovoltaics, biomass gasification began to incur.

In every waste heat recovery applications, there is a variation in the design of TEG heat recovery assembly. In general, a TEG assembly comprises of a heat collector, TEG module and a heat sink in such a way that the TEG module is sandwiched between the heat collector and the heat sink. Heat collector receives heat from the waste heat source which is conducted to the TEG module. The heat sink attached to the TEG module is at cold temperature which is sufficient enough to maintain a temperature difference. The temperature difference created across the TEG module produces electrical power. The design of TEG assembly is a critical aspect which includes selection of TEG module, design of heat collector and heat sink. The performance of TEG assembly is generally investigated in terms of production of power with respect to temperature difference achieved. Higher the temperature difference, higher is the power output and hence much significance is placed in the design of heat collector and heat sink.

Keeping this discussion in mind, the Chapter details the review of the application of TEG in recovering waste heat from different applications from Section 2.2 to 2.5 which include waste heat recovery from IC engine-driven vehicle, industries, other transportation vehicles, and hybrid TEG-renewable energy. The concept of power production using TEG is establishment of a temperature difference. The purpose of the review of TEG applications in utilizing heat from different sources is to understand the governing parameters and design aspects in power production of TEG.

The detailed review of application of TEG in biomass cook stove is discussed exhaustively in Section 2.6 and categorised into (i) heat collector, (ii) heat sink, (iii) selection of TEG module, (iv) performance testing of TEG integrated cook stove, and (v) economics of TEG integrated cook stove.

2.2. Application of TEG in IC engine driven vehicle

In vehicles, several research works on waste heat recovery from exhaust gas using TEG were performed. A typical IC engine driven vehicle exhaust TEG (ETEG) system consists of four units: heat exchanger, TEG modules, heat sink and power conditioning unit (PCU). Exhaust gas from the exhaust manifold passes through the heat exchanger. The hot side of the TEG modules receives heat from the surface of the heat exchanger whereas the heat sink, which can be either liquid cooled or air-cooled cools the cold side of the TEG modules. Generated electrical power because of temperature difference across the TEG modules flows into the power-conditioning unit (PCU) and gets stored in the battery. The PCU matches the generated electrical power with the vehicular electrical system.

Several studies had analysed a number of performance parameters (*viz*., engine type, engine rated power, type of TEG module used, number of TEG module, efficiency of ETEG and TEG, exhaust and coolant temperature and power output of ETEG) of various ETEGs implemented in different type of vehicles such as light passenger vehicles, sports utility vehicles and trucks.

Power output of 35.6W was obtained at temperature difference of 557ºC from a 3000c.c. gasoline engine from an ETEG comprising 72 modules (prepared from *p-type* and *n-type* thermoelectric (TE) elements from B and P doped Si_2Ge sintering bodies), at a system efficiency of 0.1%. Twelve blocks of module (3 modules/block) were equipped on both sides between a rectangular cross sectional exhaust pipe (pipe material: SUS304) and two numbers of water-cooled heat sink (sink material: Aluminium) [6]. In another work, researchers used 6 Bi_2Te_3 TEG modules on a 3696c.c. gasoline engine with hot side and cold side temperature maintained at 230ºC and 30ºC, respectively. The output power from this system was 42.3W [7].

An ETEG was designed with an overall dimension of 330mm ×273mm ×216mm and weight of 39.1kg comprised 16 Bi_2Te_3 modules (Model: HZ 20) mounted on both sides (8 modules/side) of a rectangular cross-section hot box. Two aluminium water jackets were used on the cold sides of the modules. A PCU is used to match the generated voltage with the vehicular electrical system at 12V and 24V. The ETEG structure was assembled at a compressive stress of 200psi. Three different performance testing of the ETEG *viz.,* i) ETEG installed without PCU, ii) fibre glass insulated exhaust pipe between the catalytic converter and ETEG and iii) insulation of exhaust pipe and ETEG installed with PCU, are carried out on a flat road. The first, second and third performance testing produced 98.1W, 130.8W and 136.3W at an observed vehicle speed of 112.65km/h [8].

Researchers at BMW obtained around 200W from an ETEG comprising 24 Bi_2Te_3 modules in a 3L BMW535i vehicle driven at 130km/h [9]

Two vehicles (*viz.,* BMW X6 and Lincoln MKT) were used for the performance testing of the ETEG. Initially, a planer ETEG was constructed that comprised of a temperature segmented TE assembly (TE assembly is divided into three temperature segment: high, medium and low) fabricated with half-heusler as high and medium temperature material and Bi_2Te_3 as low temperature material. However, the planer design is improved to a cylindrical design to eliminate issues relating to thermal contact resistance between the heat exchanger and the interface material as well as thermal expansion issues. The cylindrical ETEG, integrated in the exhaust system generated a peak power of approximately 450W under vehicle road test for BMW X6 driven at 125km/h and around 225W for Ford Lincoln driven at 120km/h [10].

Four identical ETEG system with 60 modules/ETEG were constructed for an IC engine rated at 108kW. Each ETEG comprised of a heat exchanger (length: 620mm and width: 310mm) and water cooling tank. The TEG modules are clamped between the heat exchanger and water-cooling tank under a pressure of 2.5kg/cm^2. The exhaust pipe of the vehicle was converted to four-channel pipe that is connected to the four heat exchangers of the ETEGs. During laboratory test performed on a revolving drum, with engine power of 51kW at 2600rpm, the group obtained a maximum of 944W of electrical power at a temperature difference of 201.7^{0}C. Under road tests, a maximum electrical power of 600W at temperature difference of 177.5^{0}C under engine power of 47kW at 2500rpm. [11].

Introduction of heat pipes (HP) with TEG for recovering waste heat is seen to be promising for the fact it reduces pressure losses of the exhaust gases and reduction of thermal resistance between TEG and exhaust gas [12]. Some researchers used HP that are partly inserted through the exhaust pipe and partly inserted to aluminium block. Heat, absorbed by the HP, was spread through the block. Hot side of the TEG modules is attached to the surface of the aluminium block. The system generated 350W using 224 commercially available Bi_2Te_3 modules [13]. A model was presented that worked in the similar principle to recover exhaust energy using HP. A total of 40 variable conductance heat pipe (VCHP) was used instead of standard HP whose evaporator side are protruded inside a square exhaust pipe and the condenser side is attached to a water cooling pipe. Thirty numbers of Bi_2Te_3 TEG modules are used that generated a maximum power of 550W at system efficiency of around 1.7% for an input power of above 30kW [14]. A VCHP-TEG system was constructed for a single cylinder diesel engine (Made: Yanmar L100N, maximum rated power: 7.5kW). The evaporator end of the VCHP were six finned copper pipes interconnected at the bottom which are connected to three copper blocks (acting as condensers) situated in the upper part of them. The evaporator part is engrossed in the pipe that carried the stream of exhaust gas. Twelve Bi_2Te_3 TEG modules (Model: RS-693-7116) are sandwiched between the copper condenser blocks and water cooling ducts with four modules in each block. Power performance test is conducted under three conditions i.e. HP pressure/temperature of *viz*., i) 1bar/100^{0}C ii) 2.7bar/130^{0}C, and iii) 6bar/160^{0}C. Optimum condition is attained at 2.7bar/130^{0}C where a peak electric power of 25W is achieved at system efficiency of around 1.2% [15]. Heat pipe heat exchanger and 8 commercially available Bi_2Te_3 modules were used in a 3L fuel injected V6 engine (vehicle: Holden Commodore). Eight thick walled water heat pipes (30^{0}C- 300^{0}C) are placed in exhaust duct of the heat recovery system. The exhaust duct inlet is connected to the car exhaust pipe outlet with an extractor at the outlet of the exhaust duct to carry out the exhaust gases. Further, a black plastic hose is connected from a fan outlet to duct where cool air is passed. The power performance tests are conducted at two engine speeds viz., 2500rpm and 4000rpm. At 2500rpm, the output electrical power is raised from 15.17W to 20.36W when the exhaust temperature at the inlet is raised from 218^{0}C to 250^{0}C. At 4000rpm, the electrical power output is 28.18W at exhaust gas temperature of 325^{0}C and cold side temperature of 89^{0}C. However, the generated electrical power increased to 37.85W when the mass flow rate of cold air on the cold side is increased bringing the cold air temperature from 89^{0}C to 54^{0}C [16].

Maximizing temperature difference is the key to an ETEG performance. From the review it is clear that design of heat exchanger and heat sink are responsible to maintain a sufficient temperature difference across TEG modules to obtain maximum power. Moreover, the temperature difference is needed to be uniform across all the TEG modules so that maximum power can be extracted. Also, the efficiency of TEG nodules is another aspect in ETEG performance which is dictated by the figure of merit i.e. ZT of TE materials. Commercialized TEG modules are made of materials of $ZT \leq 1$. A concern of these TEG materials is its low conversion efficiency. Majority of the reported work are being carried out using TEG modules with $ZT \leq 1$ and hence low efficiency in the overall ETEG system. Technology advancement in the field of nanoscience has paved way in the development of high ZT materials [17-20]. However, commercialization of such materials is yet to be realized.

2.3. Application of TEG in waste heat recovery in Industries

Waste heat is a by-product in industrial processes. More often this heat is released into the atmosphere. However in some cases, the heat is reused either in conversion of electricity by Steam turbines, Stirling, Rankine or Brayton engines or used in heating networks. There are various literatures that reported the use of TEG in recovering waste heat form industries.

The feasibility of using TEG in recovering waste heat from Portland cement manufacturing process was studied using a simulation model. It was assessed that around 10-15% of heat (i.e. 10MW) is lost from the surface of rotary kilns to the atmosphere. Twenty coaxial shell around the 20 rotary kilns are modelled with 3480 Bi_2Te_3-PbTe hybrid TEG modules that showed a potential power output of 210kW per unit [21].

JFE Steel Corporation, Japan implemented a 10kW Bi_2Te_3 TEG system comprising of 896 TEG modules using radiant heat from continuous casting slabs. 9kW of electricity output is recorded at a slab temperature of 915^{o}C [22-24].

Commercialized Bi_2Te_3 TEG modules were used on a 2m × 1m rectangular plate to recover waste heat from cement rotary kiln. The rectangular plate was mounted parallel to the rotary kiln centreline 10cm away from the kiln. The system was capable of generating 214.3W of matched power which is used to light LED lamps [25].

KELK Ltd. carried out field tests at a carburizing furnace of Komatsu Ltd., Awazu Plant using 16 Bi_2Te_3 TEG modules. About 4kW of heat was received by the hot side of TEG which resulted in a maximum power output of around 214W at an efficiency of 5.3%. However, the power required to cool the TEG cold side was not provided [26].

The space available for waste heat recovery in industrial processes is large compared to what is available in IC engine exhaust pipe. Thus, large quantity of TEG modules can be mounted to generate power in thousands of watts as was obtained in a casting slab industry [22-24]. TEG conversion efficiency is also an issue in waste heat recovery application from industries which is primary caused by low *ZT* TE materials in TEG module.

2.4. Application of TEG in other transportation vehicles

In addition to vehicular IC engine waste heat recovery, TEGs were also identified as a potential technology to recover waste heat from turbine engines of helicopters and jet engines from aircrafts. A research carried out by Boeing Research & Technology showed a potential for US commercial planes to save up to 0.5% (economic benefits of US$ 12M) of fuel reduction using TEG [27].

2.5. Hybrid TEG-Renewable energy

The application of TEG had also been extended to renewable energy technologies. Solar TEG utilizes sun's heat as heat source. The performance of a double pass thermoelectric solar air collector using concentrated solar radiation from a flat plate collector was tested and 2.1W of electrical power was produced [28]. Another test using a parabolic dish concentrator was also carried out by the same group which collected heat for a commercial TEG module. The set up generated a power output of 1.4W [28]. In a study, glass evacuator tube solar concentrator was combined with TEG. Heat was transferred from heat pipe absorbed within the evacuated tubes to a water channel. The hot side of TEG was attached to heat pipe and the cold side is attached the water channel thus behaving as a heat exchanger. The system behaved as a CHP system [29, 30].

The application of TEG and phase change material (PCM) on solar power generation was also studied. During day time, solar energy was used as heat source for the TEG whereas during night PCM, which stores heat, was used as heat source. A replication of sun by using a heater, 8 Bi_2Te_4 TEG modules and D-Mannitol (melting point: 130-200^{o}C) PCM were used for the study. The cooling system for TEG was based on the principle of thermosiphon. The system generated a peak power of 0.46W at a heat input of 110W (equitable to 5.5kW/m^2) [31].

A theoretical study on the performance of combined solar PV TEG system was carried out using four different types of commercialized PV modules (viz. crystalline Silicon (c-Si), amorphous Silicon (a-Si), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe)) and a single Bi_2Te_3 TEG module. The TEG was mounted directly to the back of the PV module. The power output and efficiency of a-Si, CIGS and CdTe with TEG was lower compared to a single unit of PV module. Whereas, for c-Si, the power output and efficiency increased with adding TEG [32].

Low grade geothermal heat was also studied by several researchers for power generation using TEG. The feasibility of utilizing and concerting the thermal energy of hot spring into electrical energy using TEG was studied. A prototype model of capacity 900W was designed which generated a total of 1.927MWh in 8996h of operation which spanned over one and a half year [33].

The feasibility of using to recover waste heat from producer gas cleaning units from biomass gasification was also tested. Producer gas exit from the gasifier at a very high temperature (300-400ºC), then undergoes cooling and cleaning to a temperature to form a mixture suitable for its downstream utilization [34-36]. Heat losses from the surfaces (radiation and convection) of the Biomass Gasification system needs to be quantified in this aspect. This heat remains unutilized and is a potential source for heat recovery applications. It is reported that the surface temperature of the producer gas cleaning system ranges from 200-360ºC [37]. In this regard, researchers had studied the prospect of recovering and utilizing this heat using TEG. In a study, the feasibility of using commercialized Bi_2Te_3 TEG modules is tested on the surface of the catalytic reactor (producer gas cleaning system) whose surface temperature was recorded to be between 473-633ºC. A maximum power of 6.1W was obtained at matched load [38].

Using TEG along with other renewable energy technologies showed prospect of generating additional output in the form of electricity.

2.6. Application of TEG in biomass cook stoves

Loss of heat from a traditional biomass cook stove is inevitable and thus, there had been attempts to recover such waste heat into electricity using TEG. Perhaps, Kilander & Bass in 1996 were the first to report about the use of TEG modules in a wood burn cast iron stove in Sweden [39]. Over the year researches on biomass cook stove was mostly concentrated in improving the performance and minimizing the thermal losses. Recently research on utilizing TEG to harvest and produce electricity from biomass cook stove have gained attention in view of the global issue of lack of access to electricity.

An extensive review on TEG integrated biomass cook stove was carried out to bring out insights in different aspects of design and performing parameters.

Since 1996, there have been successful attempts of electricity generation from stove through integration of TEG in places like Lebanon, Thailand, France, Malawi, Iran and India as could be seen in Table 2.1. Majority of these attempts reported to generate 1 to 10W of electricity under a wide range of design and operating conditions.

From the fundamental theory of TEG as presented in Eq. 1.7 of Chapter 1, power output from a TEG is dependent on the temperature difference between the hot and cold side of the TEG module. In order to obtain higher power output, hot side temperature and temperature difference should be higher and the temperature on the cold side should be as low as possible. Commercialized TEG modules can operate continuously at temperature as high as 300ºC, beyond which TEG modules are likely to rupture and fail to produce power. Additionally, the voltage output and current output from a TEG module vary with temperature difference, In order to regulate the voltage output and power electrical appliances an additional electronic management system is required. Economic evaluation is also an important aspect for TEG integrated cook stove in order to determine its applicability.

Thus, the thermal design i.e. heat collecting unit and cooling system (heat sink), selection of a suitable TEG module and development of an electronic management system are essential in a TEG integrated biomass cook stove. A comprehensive categorised review on (i) heat collector, (ii) heat sink, (iii) TEG module, (iv) performance testing of TEG integrated cook stove, and (v) economics of TEG integrated cook stove is presented.

2.6.1. Heat collector

In order to maximize power output from TEG, temperature at the hot side of TEG should be higher but within the safe limit of TEG module. The temperature inside the combustion chamber may be as high as 600ºC while TEG modules operate within 330ºC. The selection of material, design and location of mounting of heat collector plate to provide sufficient heat for TEG plays a crucial part.

An aluminium plate of 1cm thickness was retrofitted on the best suited location on a cast iron made wood fired stove i.e. where the temperature on the side wall was at maximum. The system used only a single TEG module and generated around 4.2W of power. The peak hot side temperature was observed to be under the safe limit of TEG module [40].

An aluminium sheet was used which was attached to a wood fired clay stove. The empty space between TEG module and hot plate and heat sink was insulated with ceramic fibre. Peak hot side temperature of 240ºC was achieved on the hot side of TEG module which generated 2.4W of electrical power [41]. In another work, a thick aluminium plate was used as the heat collector plate in an improved biomass fired stove manufactured by Plane`*te Bois* of France. Four TEG modules were used which were installed between the aluminium plate and a water tank [42]. Application of extended surface as heat collector was used in several works. In one such research, a stainless steel (SS) rod was welded onto a SS plate where the TEG module was clamped. The rod was inserted into the combustion chamber of a portable metallic biomass cook stove. Heat collected by the rod was conducted to the SS plate from where the TEG module received heat. A peak temperature difference of 240ºC was recorded with hot side temperature within the safe limit of TEG module [43]. The feasibility of utilizing a hot plate made of SS with five probes to collect and deliver heat to TEG module in a portable clay cook stove in India was investigated. The heat plate was capable of delivering sufficient heat to the TEG which generated electricity in the range of 6-10W [44-46]. An improved stove, *chitetezo mbaula stove*, was used to integrate TEG assembly where TEG module was clamped between two copper plates (5cm × 5cm × 0.3cm). Three copper rods of 0.8cm in diameter, welded to the hot side copper plate were protruded into the centre of the stove combustion chamber. Five of such cook stoves integrated with TEG were successfully deployed in a village in Malawi for 80 days [47-50]. Several researchers in Iran integrated 21 TEG modules around the walls of a wood fired stove. Each TEG module was attached to a 5cm long aluminium spacer. Both the sides of the aluminium spacer was polished to reduce thermal contact resistance between the TEG hot side and stove body. The TEG module was attached to the spacer with clamp generating a total of 430kg clamping force for maximum power generation [51].

Overall, heat collector used was either metallic plate or metallic plate with extended surface. In each of the design, no information on TEG module failure was reported which signifies that the peak side temperature received was within the safe limit of TEG module. However, for maximum hot side temperature, information on identification of ideal location for positioning the heat collector plate was missing which needs attention.

2.6.2. Heat Sink

According to several reports [52, 53], the design of the cooling system or the heat sink takes the maximum advantage of TEG characteristics and maximize temperature difference. There are four different designs of heat sink on the basis of type of cooling fluid and mode of convection. They are (i) natural convection air cooling (NCA), (ii) natural convection water cooling (NCW), (iii) forced convection air cooling (FCA) and (iv) forced convection water cooling (FCW).

As the name suggests, NCA utilizes the temperature gradient in air resulting in buoyant forces. Several researchers adopted the principle of NCA as cooling mechanism for TEG. An air cooled aluminium finned heat sink was used on the cold side of the TEG module which could not generate sufficient temperature difference. In order to achieve maximum temperature difference, a thermosiphon based heat sink was used on the cold side of the TEG. The peak temperature difference achieved was in the range of 70-80ºC [40, 54]. Air cooled aluminium finned heat sink was also used in a biomass cook stove thermoelectric generator (BITE) system. A maximum temperature difference of 150ºC was obtained which generated 2.4W of power [41].

In NCW, water reservoir in direct contact with cold side of TEG was used as heat sink. One of the advantages of such cooling system is that heat rejected from TEG was utilized to heat the water which makes the system a cogeneration unit. A water storage tank was used as heat sink for four TEG modules in an improved biomass fired stove manufactured by *Plane`te Bois* of France. During experiments, a maximum temperature difference of 160ºC was obtained that generated 7W of electrical power [42].

FCA is the most widely used cooling mechanism for heat sink in a TEG integrated cook stove. Here, the heat sink is cooled by air from an externally powered fan which draws power either from TEG or an external electric source. It is important to mention that addition of a fan not only cools the heat sink but also provides air required for combustion. The first known TEG integrated biomass cook stove used a fan cooled aluminium finned heat sink [39]. Aluminium finned heat sink cooled by a DC blower was used in a portable metallic TEG integrated biomass cook stove where a peak temperature difference of 240ºC was achieved across the TEG module [43]. A finned aluminium heat sink cooled by a 1.4 W DC fan was used on the cold side of TEG module in a portable clay stove in India. The power produced by the TEG module was used to run the DC fan and other electrical needs [44]. In another work conducted for rural areas of Malawi, the cold side of the TEG module was thermally connected to a commercial CPU heat sink. The idea was to power the fan of CPU heat sink from the TEG module. A maximum temperature difference of 210ºC was achieved which generated a peak electrical power of 5.9W [47-50].

Chinese TEG manufacturing company had developed a TEG cook stove with fan cooled heat sink [55]. Commercial TEG integrated stove such as BIOLITE, TEGOLOGY and DEVIL WATT are also available which uses FCA to cool the cold side of TEG module [56-58].

In FCW, water flow using a pump through water cooling blocks is used on the cold side of TEG module. In most of vehicular exhaust TEG system, such cooling mechanisms are used. In one work, the cold side of TEG module was attached to water filled aluminium cubic channel having dimensions of 6cm × 6cm × 2.5cm. Each channel comprised of two pipes (incoming and outgoing) on opposite sides. The aluminium cubic channel in a row was arranged in such a way that the outgoing pipe of one channel connects the incoming of the other and likewise. The water passing through the channels extract heat from the cold side of TEG modules. The peak cold side temperature recorded is 48.3ºC [51].

From the review, it is observed that NCA is not sufficient to maximize temperature difference across the TEG nodule. However, FCA has several potential benefits starting from cooling the cold side of TEG to improving combustion of cook stove. In NCW, the twin benefits i.e. electricity and hot water is a serious advantage over other cooling system. Further, heating of TEG can be avoided in NCW as the maximum temperature that can be achieved by water in heat sink is 100ºC. Among all the cooling mechanisms, FCW and FCA showed maximum achievable temperature difference. However, the use of external power to operate FCW and FCA adds a complexity of additional maintenance and economics.

2.6.3. Selection of TEG module

The choice of TEG which has bearing on cost and performance has been a major consideration. The TEG module is the most essential component in a TEG integrated biomass cook stove that converts heat to electricity. As mentioned previously, the temperature in the combustion chamber can reach as high as 600ºC while majority of commercialized TEG modules using Bismuth Telluride (Bi_2Te_3) are developed to operate within 300ºC. TE materials that can operate beyond 300ºC are made of Lead Telluride, hybrid bismuth telluride-lead telluride and Calcium/Manganese Oxide [59].

There is a wide range of choices including Thermonamic (China), HiZ (USA), Marlow (USA), Komatsu (Japan) and TECTEG (Canada) suitable for the application in the cook stove [60-64]. However, TEG modules from Thermonamic and TEGTEG can operate at temperature as high as 300ºC. Thermonamic TEG modules of sizes varying from (4×4) cm^2

to (5.6×5.6) cm^2 with a claim that their TEP and TEHP models could generate up to 21.6W corresponding to temperature difference of 270ºC and with maximum operating temperature of 300ºC.

In all the researches on TEG integrated biomass cook stove, Bi_2Te_3 based TEG modules were used for its ease in availability and affordability [59, 65]. Further, the TEG module for application in heat to electricity conversion must have higher *ZT*, better contact properties, stable with simplicity in design [66]. It can be observed from Table 2.1 that TEG modules of different manufacturers were used for heat to electricity conversion. Single HZ-20 Bi_2Te_3 TEG module was used which generated a peak power of 4.2W at 256ºC [40]. Thermonamic, China made TEP1-1264–3.4 was used with potential to operate continuously in the range of 300ºC in a fire clay wood stove. The TEG generated 2.4W [41]. Two different types of Bi_2Te_3 TEG modules (HZ-9 and TG1208-1LS) were used in an Indian portable cook stove which generated a peak electrical power output of 6W [44].

The operating temperature is an important factor as it determines the durability of TEG module. From the review, Thermonamic and TECTEG made TEG modules which operate in the range of 300ºC are suitable for cook stove applications.

2.6.4. Performance testing of TEG integrated cook stove

Performance testing of a TEG integrated cook stove is carried out to investigate the production of power with respect to increasing temperature difference, ability of TEG to operate electronic appliances and charge battery powered devices. Majority of the attempts reported to generate 1 to 10W of electricity under a wide range of operating conditions. The performance of TEG at matched load and as a battery charger can be found in several researches on TEG integrated biomass cook stove.

The power output of a TEG module is maximum at matched load i.e. load resistance equal internal resistance of TEG module. Power output is reported to change with change in load resistance. Power output of TEG is observed to increase with increase in load [41]. Around 4.5W (load voltage: 4.5V and current: 1A) of matched load power was obtained from a TEG module at temperature difference of 240ºC. The TEG module was rated at 5W of power at similar temperature difference. The change in internal resistance of the module with temperature was reported to have reduced the power output compared to rated value [43].

The performance of TEG in charging battery was investigated in several studies. In one such study, two types of TEG modules (HZ-9 and TG1208-1LS) were used in three different ways (i.e. one HZ-9, two HZ-9 in series and one TG1208-1LS) for the testing phases. Two different electrical topologies were tested (viz. (i) DC fan connected to battery charged by TEG and (ii) DC fan directly connected to the TEG) for generating power. Both HZ-9 and TG1208-1LS generated a maximum of 6W of power. However, when two HZ-9 were used in series, a maximum of 10W was generated. Clean combustion was attained during the first electrical topology but with limited lighting power. However in the second topology, a maximum of 4W of lighting was achieved using two HZ-9 modules [44]. A $LiFePO_4$ battery was used to store the generated power, for which a charging circuit was developed. The stove produced about 3.9Wh of electricity for every hour of usage, 3.1Wh of the generated power was stored in the battery. A total of three hours of stove usage was enough to completely charge the battery. Five of such stoves with temperature and voltage data loggers were distributed among five households of Balaka district in Malawi for a period of 80 days. Each stove was equipped with temperature and voltage data logger. A maximum of 230 times of stove usage was recorded with maximum electricity generation of 700Wh. However, the electricity generation capability has been lesser (2.5 to 8Wh/day) from an average of 8h stove usage as compared to laboratory conditions (9Wh/day) from 3h of stove usage. Higher ambient temperature and users cooking behaviour was believed for the lower electricity generation [47-50].

Table 2.1 Review of the applications of TEG in cook stove

Place of work/ Reference	Type of stove	Model/number of module used	Type of Heat sink *	ΔT, (ºC)	Power, W
Lebanon, [39]	Cast iron made Wood stove	HZ-20/1	NCA	256	4.2
Thailand, [41]	Fire clay made single pot wood/charcoal fired cook stove	TEP1-1264–3.4/1	NCA	150	2.4
India, [43]	Metallic (SS made) single pot cook stove	TGPR-5W-5V-35S/NA	FCA	240	4.5
France, [42]	Multifunction stove	TEP1-12656-0.6/4	NCW	120	7.6
India, [44]	Single pot biomass cook stove	TG1208-1LS/1	FCA	NA	6.0
		HZ-9/1		NA	6.0
		HZ-9/2		NA	10.0
Iran, [51]	Traditional wood/coal stove	TEP1-12656-0.6/21	FCW	NA	166[a]
Malawi, [47-50]	Clay cooking stove	TEG 12610-5.1/1	FCA	210	5.9

*NCA: natural convection air cooling; FCA: forced convection air cooling;
NCW: natural convection water cooling and FCW: forced convection water cooling
[a]7.9W is the power generated by each module.

2.6.5. Economics of TEG integrated cook stove

In order to understand the applicability of TEG integrated cook stove designed to minimize the issues of clean cooking and inadequate access to electricity, economic evaluation is important.

A cost analysis was carried out to compare the cost of energy supplied by two 1.5V batteries to power a 1.8W bulb with a 2.4W biomass cook stove thermoelectric generator (BITE). If operated continuously for 365 days, a payback period of 0.74 year for the TEG stove was estimated [41]. While purchasing components for 100 units for assembling 6W TEG integrated cook stove, the unit cost of around 143 US$ was reported [42]. Further, varying costs of TEG integrated cook stove as 93US$, 107US$ and 186 US$ for three design configurations with output power as 6W, 6W and 10W, respectively were reported [44]. The cost of a 4.5W TEG integrated metallic cook stove was compared with a forced draft biomass cook stove. The cost of the former was observed to be lesser compared to the latter with an added advantage of using power generated by TEG to induce forced draft [43].

Commercialized TEG integrated biomass cook stove are available but at a sufficiently higher price range of 129US$-725US$ [56-58].

TEG module bears the majority of the cost in a TEG integrated cook stove. With higher initial investment, the payback period of such stoves is also high. However, there is a possibility of added benefits which can be obtained from a TEG integrated cook stove. Since in most of the researches, TEG is integrated with improved biomass cook stoves, there is a possibility of economic benefits associated with firewood savings, kerosene savings due to provision of electricity reduction and time saving in cooking.

To understand the economic benefits, field testing of TEG integrated cook stove is required which is absent in most of the reported literatures apart from a test carried out in Malawi where five TEG integrated cook stoves were deployed and performance was recorded for a duration of 80 days [48-50]. There are no reported researches on TEG integrated cook stove that discusses the economic benefits the stove provides. However, reports on economic benefits provided by improved cook stove can be found. The following section discusses the procedure and results of economic benefits an ICS provides.

2.6.5.1. Economic analysis of cook stoves

The adoption of a technology (say, improved cook stove) is possible if users find benefits over their existing cook stove. These benefits can be either from firewood savings, kerosene savings and time savings. A comprehensive costs and benefits analysis is required to determine the applicability of an ICS. There are several studies that adopted different methodologies to evaluate the value of costs and benefits of an ICS.

The economic benefits of Patasari cook stove dissemination was investigated in Purepcha region of Mexico. A comprehensive evaluation of economic benefit in terms of cost avoided from firewood savings, income generation from cooking rime saving, local and environmental cost avoided in afforestation and cost avoided from health check-up was done. A cost benefit analysis was also done to determine the net present value of the project and benefit to cost ratio at different rate of discount (3%, 10%, 15% and 20%) and for two specific duration of the dissemination project (7 and 14 years). Avoided costs from firewood savings followed by costs saved from reduction of health impacts contributed to highest share in economic benefits at 53% and 28%, respectively. The results obtained from the economic evaluation suggested that Patasari cook stove was a viable economic option particularly for poor inhabitants as benefits of 11US$ and 9US$ on investing 1US$ was achieved [67].

An economic analysis of improved household cook stove dissemination program was carried out in Uganda that distributed around 211220 rocket lorena cook stoves by the end of 2006. The economic analysis investigated the economic benefits of rocket lorena cook stove owners and economic benefits obtained from health and environment at global and national level. A comparison of benefits and costs associated with the dissemination was also provided. For the economic evaluation, cost benefit analysis and cost effectiveness analysis were carried out. The cost benefit analysis included benefits derived from costs avoided from firewood savings, time saved in cooking, reduced health costs, preservation of forests, reduction in greenhouse gases and benefits from improved soil quality. The net present value of benefits was observed to be higher compared to the costs incurred in the project. Considering all the benefits, 1US$ of investment yielded 29US$ in returns. The benefit to cost ratio was also significant if firewood savings was considered, as 15US$ in returns was yielded for 1US$ of investment [68].

Likewise, costs and benefit analysis of efficient institutional cook stoves was also investigated in Malawi. The economic analysis comprised of cost benefit analysis and effectiveness analysis in addition to other macroeconomic criteria calculation. A period of 10 (2005-2014) years at a discount rate of 3% is selected for the analysis. The cost benefit analysis comprised of only the benefits derived from costs avoided from firewood savings, preservation of forest resources and reduction of greenhouse gases. More than 50% of the total benefit was from firewood savings followed by preservation of forest resources and greenhouse gas reduction. It was estimated that investment of 1US$ yielded a return of 2.7US$ considering firewood savings alone. Whereas, considering all the benefits the return in investment was 5US$ for every dollar of investment. Also, the cost effectiveness analysis showed that investment of 1US$ resulted in firewood savings of 93kg [69].

The costs and benefits associated with improved cook stoves were evaluated and ICS's implications on health, forest reserves and climate were also assessed. The costs and benefit analysis of six stoves viz., (i) improved wood burning stove, (ii) traditional charcoal stove, (iii) improved charcoal stove, (iv) kerosene stove, (v) LPG or propane gas stove, and (vi) electric stoves was compared at individual household level. The costs included capital cost, operation and maintenance cost, fuel cost, cost of familiarization with new stove technology etc. whereas the benefits included cost avoided from reduced diseases, reduced cooking time, reduced in house exposure to soot and smoke, improvement in household status from owning an ICS and reduced greenhouse gas emissions. It is reported that time saved in cooking is a critical factor in achieving high returns from improved cooking methods compared to traditional biomass cooking. Also reported was the benefit associated in change of fuel type and stove type have high influence on net benefits from improved charcoal stoves to LPG and electric stoves [70].

A model was developed to analyse the time saved in firewood collection when transition was made from traditional biomass cook stove to improved biomass cook stove in a rural village of Assam, India. Switching from traditional biomass cook stove to improved cook stove, sufficient time and avenues for employment generation opens up. Around 828h was invested to collect firewood during traditional method of cooking which fell to 345h in case of improved cook stove cooking [71].

Fuel and cost savings of improved cook stove distributed in Chad and Cameroon border were analysed and compared among three stove models namely, (i) three stone fired, (ii) ceramic improved cook stove and (iii) centrafricain improved cook stove. The performance of these cook stoves was studied using Water boiling test and controlled cooking test. With improved efficiency, the improved stove models used 31-32MJ of energy compared to 43MJ in three stone fired stove, thus achieving 25% of fuel savings compared to three stove fired cook stove. The fuel costs attributed to ceramic and centrafricain stove during water boiling tests were 0.09US$ and 0.1US$, respectively compared to 0.14US$ in three stone fired stove. During controlled cooking tests, improved versions of cook stoves showed better cooking performance as improved versions consumed less wood (1.5-1.6kg) per meal preparation compared to more than 2kg in three stone fired stove. Specific fuel consumption of ceramic and *centrafricain* model was reported to be 24% and 35% lower compared to three stone fired stoves. Overall with higher life span of cooking stove, the benefits were estimated to be higher. Although the initial investment of *centrafricain* model is higher, with longer life span, an estimated saving of 28US$ per household was reported with a payback period of 9 months [72].

A model named levelized cost of cooking a meal (LCCM) was used to compare the cost of cooking a meal associated with (i) three stone fired cook stove, (ii) traditional charcoal stove, (iii) improved wood cook stove, (iv) improved charcoal cook stove, (v) LPG stove and (vi) electrical stove in Nyeri, Kenya. The model used stove cost, fuel cost, energy required for cooking a meal, stove efficiency, operation and maintenance cost, lifetime of stove, amount of meals cooked in the lifetime and discount rate as input variables to determine the LCCM. Results indicated that with increased usage of improve wood and charcoal stoves, LCCM of households reduces. However, the transition to LPG and electric stove is not up-front since the price of LPG and electricity in Kenya is high [73].

2.7.Summary

Application of TEG for electricity production utilizing heat from different applications are reviewed. Information on the review of evolution and current status of TEG in recovery of waste heat from different applications have been useful for the present research. Besides, the understanding of the technical factors of TEG assembly of a TEG integrated cook stove, review on its utility linked with the economy of operation were useful for implementation of the current research.

Overall, it was observed that metallic heat collector, either a plate or plate with extended surfaces are effective in collecting waste heat. The location of positioning of the heat collector plate is an important consideration in order for the TEG to receive maximum heat, but within its safe limit. FCA and FCW are superior to NCA and NCW in cooling the cold side of TEG, However, to achieve multiple benefits and reduce auxiliary power consumption, NCW is ideal. Selection of TEG module which can operate within temperature range of. 300 ºC to 400 ºC (available for waste heat collection) such as, Thermonamic and TECTEG are useful. Additionally, long duration of field testing is essential to understand the economic merit and practical usefulness of the TEG integrated cook stove.

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