CHAPTER 1

Introduction

According to International Energy Agency, energy access is defined as,

"*a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially and then an increasing level of electricity over time to reach regional average*" [1].

Access to modern forms of energy sources is essential to fulfill basic social needs and drive economic growth for livelihood improvement. Modern energy services such as electricity and modern cooking fuel effect work productivity, health, education, and communication services. However, there is a wide variation in energy access among people living in different regions. The following sections discuss the issues of energy access and efforts through R&D and government to resolve them.

1.1. Dominancy of solid fuel for cooking

An estimated 2.7 billion people, majority of whom live in rural areas, still use biomass fuels such as firewood, crop-residues and cow dung cake in traditional/3-stone fired cook stoves to cook their food. There are different versions of traditional cook stoves in different countries with variations in their design, but associated with similar disadvantages such as low thermal efficiency (<10%), indoor air pollution and drudgery to collect fuel [2-7]. According to World Health Organization (WHO), around 4 million people die prematurely from diseases (viz. ischemic heart disease, chronic obstructive pulmonary disease and lung cancer) attributable to indoor air pollution [8-11]. Incidentally more than one-third of deaths (3.8 million) from indoor air pollution occur in regions of Asia (India, China, Bangladesh, Pakistan and Indonesia) and Africa (Congo, Ethiopia, Nigeria and Angola) [12-13].

In India, current metrics state that more than 700 million (~51% of total population) depend on biomass cooking [1]. Although there has been a transition from biomass to cleaner fuel such as LPG in the recent years owing to Government of India's clean cooking initiative, it is projected that 580 million will still be dependent on biomass cooking by 2030 [1,14].

Most of the traditional biomass cook stoves in India are fixed to the ground and made of locally available materials (mud, clay and cow-dung) also known as fixed clay cook stove as shown in Fig. 1.1. These cook stoves have low thermal efficiency in the range of 8-10% [4, 5]. Lower thermal efficiency is due to energy loss resulting in higher fuel consumption requiring additional time for fuel collection. It is reported that women in India spend 374h a year to collect firewood [15]. The inefficient burning of biomass in fixed clay stove also leads to indoor air pollution. In India, generally women do most of the cooking and therefore are excessively affected by household indoor air pollution of high particulate matter such as black carbon [16-18].

Further, owing to higher thermal mass and low thermal conductivity of the stove material, fixed clay cook stove stores substantial amount of heat within the body. An estimated 10-15% of the input fuel energy is stored and lost as waste heat in the stove body [19].

Fig. 1.1 Different versions of fixed clay stove (a) fixed clay cook stove with elevated platform, (b) cooking practice in three stone fixed clay coated cook stove, (c) three stone clay coated fixed cook stove

1.2. Research and Development efforts to improve thermal efficiency of cook stove

In general parameters such as, ignition, air flow, and stove materials affect the performance of stove operation [20, 21]. Some highlights of these aspects are presented below.

1.2.1. Ignition

Firewood requires sufficient temperature in the range of 300-500ºC to ignite. As long as there is sufficient supply of air and the temperature in the combustion zone is high, firewood will ignite and burn steadily. During combustion, combustible gases and particulate inorganic carbons (PICs) are released from firewood. In order to ensure cleaner combustion, combustible gases and PICs must ignite and combust before exiting from the stove. At the combustion zone, firewood during the ignition phase are at low temperature and as a result formation of PICs will be promoted. Thus, research in reducing ignition time of firewood took place. Fast charcoal ignition was possible using well insulated combustion chamber, metal grate and opening that improves air flow in cook stove [22]. Selection of proper fuel such as charcoal briquette, corn-stover briquette and other agro-residue could also improve ignition with steady combustion [23, 24].

1.2.2. Air flow

Oxygen in air reacts with firewood inside the combustion chamber to produce heat and combustible gases. When these combustible gases get heated, its density decreases in comparison to air at room temperature. The difference in density caused by temperature difference causes a natural draft of air into the combustion chamber. More the production of combustible gases more is the amount of air drawn inside the combustion chamber of cook stove. In biomass cook stoves, supply of air takes place in two modes i.e. primary and secondary depending upon the location of fire. Primary air directly enters the combustion chamber and reacts with fuel whereas secondary air enters from top of the combustion chamber to react with PICs present in exhaust gases.

Most of traditional cook stoves are natural draft or free convection driven cook stoves. Inability of sufficient air flow inside the combustion chamber leads to incomplete burning of fuel. Use of externally powered fan to provide high velocity jets of air which mixes air, fuel and flame is proposed and adopted by many commercial rocket and gasifier stoves

[21]. Such fan assisted cook stoves are reported to reduce fuel consumption by 40% and efficiency in the range of 30% [25, 26]. Also, the geometry of air flow path such as narrow (small diameter riser) flow path and fuel grate with small opening can improve performance of biomass cook stove [27].

1.2.3. Stove materials

The function of stove materials is to cause heat transfer through different parts of the stove besides providing structural strength to operate. Ideally, it is expected that all heat generated would be transferred to the pot, however, heat flows different paths within the stove, to the pot and the surroundings as losses. Experiments on three stone fired cook stove stated that less than 10% of energy generated is transferred to the pot whereas more than 90% is lost to the surroundings [20]. Whereas, for an insulated cook stove with pot skirt, 35% of energy generated is transferred to the pot and 65% is lost to the surroundings justifying the importance of stove material [20]. Further, in high thermal mass fixed clay biomass cook stove, 10-15% of heat generated is stored within the stove body and lost as waste heat [19]. Use of appropriate cook stove material to reduce heat losses into and out of the cook stove body has been focus of some recent researches.

Choice of insulation material have a significant impact on cook stove thermal efficiency [20]. Transitioning from high density and thermal mass insulating materials such as concrete and clay to low density, low thermal mass materials like perlite can increase thermal efficiency by 25% [20]. Metallic stoves constructed from steel, cast iron and sheet metal are designed for quicker operation. The low specific heat of these materials lets the heat to transfer quickly and in the process, the cooking pot receives heat from the material as well. Some of the recent metallic cook stoves include Envirofit G-3300, Philips natural draft stove HD4008, Vikram and Harsha [25, 28, 29]. Some stoves are prepared using cement as the construction material such as the Laxmi, Astra and Priya stoves under National Programme on Improved Chulha (NPIC), India and the Mirt stove, Ethiopia that reported thermal efficiency up to 40% [30, 31].

Hybrid type of materials such as mud, cement, ceramic and metal are also used in StoveTec, Philips power stove HD4012 and Oorja where the combustion chamber is made of ceramic and outer body is made of metal [26, 32, 33].

1.3. Government initiatives to disseminate efficient cook stoves

Realizing the issue of low thermal efficiency and indoor air pollution, several research laboratories (Aprovecho Research Center, USA; Environmental Protection Agency, USA and Lawrence Berkeley National Laboratory, USA), National governments (Ministry of New and Renewable Energy, India; National Improved Stove Program, China), international organization (WHO and USAID), and NGOs (Clean Cooking Alliance) have taken the initiative to develop, disseminate different versions of biomass improved cook stoves (ICS) [34-39].

Since the early 1970s, international organization and NGOs have been implementing improved cook stove programs [39]. Among these, the Indian National Programme on Improved Chulhas (NPIC) is the largest projects which developed 62 different ICS models and disseminated 35 million ICS across India till the early 2000s [40, 41]. In 2010, Ministry of New and Renewable energy, India launched the National Biomass Cookstove Initiative (NBCI) to develop efficient cleaner cook stove and deploy at households to replace traditional biomass cook stove [23]. The initiative disseminated several cook stoves with versatility of fuel types (viz., firewood, cow dung, agro residues, twigs, briquettes and bagasse) having thermal efficiency in the range of 30-50% [42].

Despite of the continuing efforts to improve the design of cook stove through R&D and government initiatives to introduce ICS, a large section of population is still relying on traditional clay made cook stove.

In addition to dominancy of solid fuel in rural areas, inadequate electricity access has been another critical concern. The following section discusses the issues of electricity access in rural areas.

1.4. Global electricity access

Sustainable Development Goal 7 states access to affordable, reliable, sustainable and modern energy for all by 2030 [43]. However, over 1 billion people still do not have access to reliable and adequate electricity [1]. More than half the population mostly concentrated in rural areas (~632 million) without electricity access resides in Sub-Saharan Africa and under 500 million in South east Asia. [1, 44] This poses a threat to wide range of development indicators viz., health, education, food security and poverty reduction. Rural energy access in the form of electricity is essential for all round development. For a country to achieve the development status, its primary priority should be to provide reliable electricity for all.

1.4.1. Status of electrification

Electrification has primarily become a rural issue rather than an urban issue as more than 95% of the urban population of the world has access to electricity [45]. It is common in rural regions where substantial percentage of population have to depend on kerosene lamps, candles and firewood for lighting. Many reports have highlighted the inconvenience caused by kerosene lamps [46-48]. School going children face the hardship during study hours from poor lighting conditions. Another issue concerning inadequate electricity access is the use electrical operated devices, such as mobile phone or battery powered light [49]. A report from GSMA stated that access to mobile phone telecommunication have overtaken the access to electricity as evident from the report that about 538 million mobile phone users in regions without access to electricity causing additional hassle for the users to charge their phone at the cost of time and money [50-52].

There have been serious efforts by national governments to achieve 100% rural electrification in most part of the world but with mixed success. For example, 20.8 million of Myanmar's rural population and about 0.9 million of Sri Lankan rural population lack access to electricity [53]. Similar is the case for Bangladesh (33.3 million), Nepal (2.86 million), Afghanistan (5.37 million) and Korea DPR (6 million) where more than 90% of the rural population lack electricity access [54-57]. The status of electricity access is worse in most parts of the Sub-Saharan Africa (SSA), where daily per capita electricity access is less than 20W [58]. For instance, the annual per capita electricity consumption of countries like South Sudan, Malawi, Congo DR, Uganda, Tanzania, Niger, Ethiopia, Nigeria and Central African Republic is drastically less than world average as presented in Table 1.1 [59]. During 27 years, government efforts to improve electricity access have resulted a progression in annual per capita electricity consumption among countries except for Korea DPR and Congo DR.

It is reported that two in every three Sub-Saharan Africa, approximately 632 million in total, lack access to electricity. Around 80% of the populations (14.8 million) in rural Malawi have no access to electricity relying mostly on traditional energy resources including candles and firewood. Major part of the daily time of the Malawi's citizen is spent for collection of fuel resources to support their basic activities [60-63]. Even in a country like South Africa, around 14% of its population (55.91 million) do not have access to electricity, majority of them are rural [64] experiencing severe inconvenience including accidents due to improper use of kerosene [46-48]. Moreover, the avenues for employment and education cease as most of the time is devoted to fuel collection for lighting and cooking in such regions.

Table 1.1 Annual per capita electricity consumption of South East Asian and Sub Saharan African countries [59]

Country	Annual per capita electricity consumption, kWh/capita/annum		
	1990	2017	% change
India	273	1122	311
Myanmar	45	193	329
Bangladesh	48	351	631
Afghanistan	-	141	-
Nepal	35	134	283
Sri Lanka	151	494	227
Philippines	361	885	145
Korea DPR	1237	600	-52
South Sudan	-	55	-
Malawi	-	102	-
Congo DR	131	114	-13
Uganda	-	70	-
Tanzania	51	95	86
Niger	-	128	-
Ethiopia	23	65	183
Nigeria	87	128	47
Central African Republic	-	36	-
World average	2125	3225	52

In India, average annual per capita electricity consumption is about 1122 kWh/capita which is lower than the world average as seen from Table 1.1. Per capita electricity consumption in some of the states in India is even lower than the national average (Table 1.2). In most parts of India, rural users with grid electricity are faced with fewer hours of electricity supply due to supply and demand mismatch in power generation companies. States like Assam, Mizoram, Nagaland, Uttar Pradesh, and Arunachal Pradesh in India have been facing the issues of unreliable electric supply (Table 1.2). Less than 18h of electricity supply is available in rural areas of these states [65]. A report on rural electrification in 2019 stated that the daily availability of electricity in a rural village in India is only 11h [66].

In Assam, (India), the annual per capita electricity consumption is 339kWh which is below the national average [66]. Low electricity availability has affected almost all sectors of economic and social importance. There has been several attempts including the use of solar photovoltaic (SPV) home light system in recent time with different degree of success in Assam [67]. Decentralized generation of electricity through SPV or other means are acceptable to local people, at least to support basic domestic needs, provided it is economic and affordable. However, SPV cannot be taken as reliable source due to inherent uncertainty of available solar radiation and also due to relatively higher system cost which is not affordable to majority of the population.

Table 1.2 Duration of electricity supply in some states in India [65]

Region	Annual Per capita electricity consumption kWh/capita	Electricity supply in rural areas, hours
Assam	339	16
Arunachal Pradesh	648	11
Nagaland	345	15
Mizoram	523	9
India	1122	-
Dadra & Nagar H	15783	
Punjab	2028	24
Gujarat	2279	24
Uttar Pradesh	585	17

Thus, it appears from the above discussion that the issues of lack of clean cooking and inadequate access to electricity have global relevance in order to provide relief and improve livelihood to the distressed people. Transitioning from energy deprivation towards clean, affordable and sustainable sources of energy is a global challenge every country must consider. United Nations (UN) has set 17 Sustainable Development Goals (SDGs) as a major step that addresses poverty, energy access, equality and climate change [43, 68]. Around 193 countries have adopted SDGs in 2015 in order to improve livelihood of people by 2030 [69].

However, seeing the current trend of growth of electricity generation and dissemination of clean cook stove, achievement of such goals appears to take some time. Therefore, some appropriate and immediate technological intervention is essential to address the misery of the people caused by energy poverty.

As discussed earlier, up to 15% of input fuel energy is absorbed and stored within the traditional fixed clay stove body during cooking [19]. The high thermal mass, low conductivity and low thermal diffusivity of the stove material cause low rate of heat dissipation through the stove body. With appropriate technological interventions to recover this fraction of heat and its subsequent conversion into electricity could lead to a broader solution for the issues discussed above. Arrangement of even nominal electricity for night time illumination and battery charging, through recovery and conversion of waste heat from cooking stove, is expected to reduce the difficulties in typical rural areas till regular and reliable supply of electricity is ensured. In the process, such technology can contribute to achieving the agenda of SDGs.

1.5. Technologies to convert heat into electricity

In principle, there are several technologies that converts heat into electricity, such as (a) Stirling engine (SE), (b) Rankine cycle (RC), (c) Brayton Engine (BE), (d) Biomass Gasifier integrated heat engine and (e) Thermoelectric Generator (TEG) (Table 1.3). However, selection of appropriate technology for heat to electricity conversion is important and has to be based on certain criterion, particularly considering the type of heat source.

SE, RE, BE and biomass gasifier heat engine are suitable for large scale applications and is not appropriate for a cook stove. Source of waste heat in traditional fixed clay stove is the heat received by the combustion chamber inner wall and TEG is the appropriate candidate in the present context. Moreover, TEG is silent in operation, has no moving parts and requires less maintenance (Table 1.3).

Table 1.3 Technologies for heat to electricity conversion

Technology	Low maintenance	Silent in operation	Longer steady state operation	Compactness	Reference
Stirling engine	×	√	×	×	[70]
Rankine cycle	×	×	×	×	[71-74]
Brayton Engine	×	×	×	×	[75]
Biomass gasifier integrated heat engine	×	×	×	×	[76-77]
Thermoelectric Generator	√	√	√	√	[78-80]

1.5.1. Thermoelectric Generator: Principle of operation

A TEG is solid-state device that operates on the principle of Seebeck effect or thermoelectric effect, discovered by Thomas Johann Seebeck in 1822, which states that a voltage (V) is produced when a temperature difference between two junctions, made from two different conductors is created. Voltage V is directly proportional to temperature difference, ΔT (ºC) $=T_h-T_c$ (T_h is the hot junction temperature and T_c is the cold junction temperature) and Seebeck coefficient, α (V/ºC) as given below.

$$V = \alpha \times \Delta T \quad (1.1)$$

A TEG module as shown in Figure 1.2 comprises of a number of n-type and p-type semi-conductors (also known as TE material) connected in series and thermally in parallel. These couples of n-type and p-type semi-conductors are packed between two ceramic plates (also known as substrates). In general, the TEG is sandwiched between a hot side heat collector and a cold side heat sink. Heat at high temperature is collected at the hot side of TEG and heat at low temperature is rejected to the heat sink while generating electricity. Higher the temperature difference from hot to cold side of TEG, higher is the yield of output power.

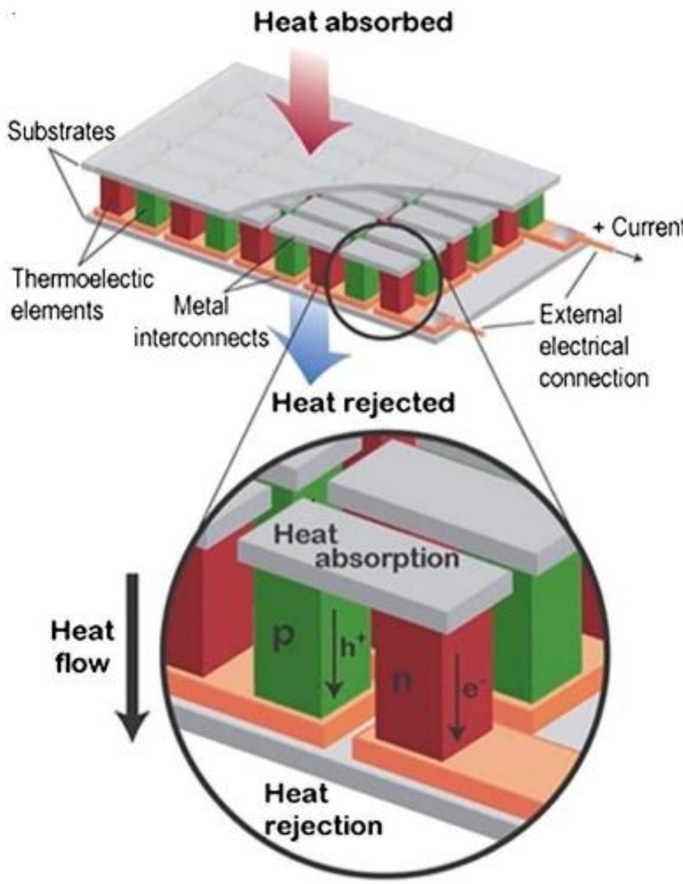

Fig.1.2 Pictorial view of a typical commercial TEG module showing different components, Adapted from [81].

The power conversion efficiency of TEG modules depends on the efficiency of TE materials. The efficiency of a TE material depends on its figure of merit, Z which is expressed as a dimensionless form ZT [82, 83]. ZT is expressed as the equation given below.

$$ZT = \frac{\alpha^2 \times \sigma}{\lambda} T \tag{1.2}$$

where, α *(V/K)*, σ $(\Omega^{-1}.m^{-1})$, T *(K)*, and λ $(\frac{W}{m.K})$ are Seebeck coefficient, electrical conductivity, absolute temperature and thermal conductivity of the TE material respectively.

ZT is an important parameter in selection of TE materials. It can be seen from Eq. 1.2, that *ZT* is directly proportional to Seebeck coefficient and electrical conductivity but inversely proportional to thermal conductivity. Commercialized TEG modules are made of materials of $ZT \leq 1$. It can be seen from Fig.1.3, that the efficiency of TE material with *ZT*=0.8 is under 7% up to a maximum temperature difference of 500ºC, whereas for TE material with $ZT \geq 2$, efficiency is more than 10% from a temperature difference starting from 250ºC.

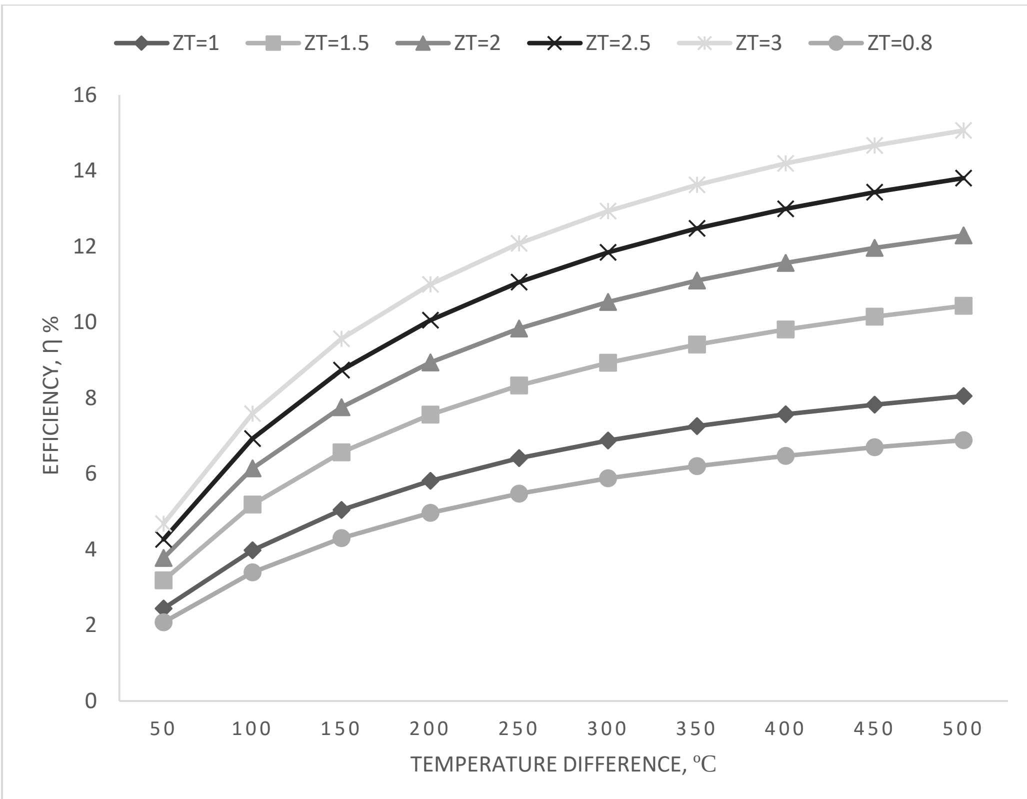

Fig. 1.3 Variation of efficiency with different *ZT* Adapted from [84]

Since a long time, TEGs using Bi_2Te_3 (Bismuth Telluride) have been in practice owing to its reasonable price. But the lower availability of Bismuth and Tellurium in earth's crust and its lower operating temperature range have compelled manufacturing companies to manufacture and commercialize TEG modules using other TE materials such as PbTe (Lead Telluride), TAGS (Tellurium Antimony Germanium Silver) and CMO (Calcium

Manganese Oxide) [85]. Table 1.4 summarizes the list of manufacturers and their commercialized modules.

Thermonamic, China [86] manufactures wide variety of TEG modules of size varying from (4×4) cm^2 to (5.6×5.6) cm^2. The TEP and TEHP series module using Bi_2Te_3 generate power output in the range of 5.3W to 21.6W at a maximum temperature difference of 270ºC (Hot side: 300ºC; cold side: 30ºC). It also markets two TEG module series of PbSnTe-Bi_2Te_3 material and single PbSnTe. The former operates at a maximum temperature range of 600ºC while the latter at 350ºC.

HiZ (USA) [87], Marlow (USA) [88] and Komatsu (Japan) [89] manufactures TEG modules using Bi_2Te_3 as TE material. The maximum operating temperature range is below 300ºC.

TECTEG (Canada) [90] markets Calcium Manganese Oxide modules and Calcium Manganese Oxide cascaded with Bi_2Te_3 that have the maximum temperature range of 800ºC and 600ºC, respectively. These modules can generate an output power of around 12.3W (at ΔT = 750ºC) and 11W (at ΔT=435ºC), respectively. Apart from these, it also manufactures a series of TEG modules using PbTe-TAGS as TE material with maximum operating temperature range of 600ºC that can generate power between 1.3W and 30W.

The selection of a TEG module for electricity conversion is critical which is dependent on factors such temperature of heat source, electricity demand at user end and cost. In a biomass cook stove, the temperature of the combustion chamber can reach as high as 800ºC [91, 92]. However, majority of TEG modules operate in the peak temperature range of 250-330ºC. There are other TEG modules which can operate beyond 600ºC but comes with sufficiently higher cost.

Table 1.4 Commercialized TE materials

Manufacturer	Code	TE material	Maximum Temperature , ºC	Output Power range, W	Remarks
Thermonamic (China)	TEP Series	Bi_2Te_3	330	5.4 – 17.6	`at ΔT= 270ºC
	TEHP Series	Bi_2Te_3	330	5.3 – 21.6	at ΔT= 270ºC
	TELBP Series	PbSnTe-Bi_2Te_3	350	21.7	at ΔT= 320ºC
	TELP Series	PbSnTe	600	21.7	at ΔT= 570ºC
HiZ (USA)	HZ-2, HZ-9, HZ-14, HZ-14HV, HZ-20	Bi_2Te_3	250	2-20	at ΔT= 200ºC
Marlow (USA)	TG12-2.5-01LS, TG12-4-01LS, TG12-6-01LS,TG12-8-01LS	Bi_2Te_3	230	2.7-7.95	at ΔT= 200ºC
Komatsu (Japan)	-	Bi_2Te_3	280	24 W	at ΔT= 250ºC
TECTEG (Canada)	TEG1 Series	Bi_2Te_3	300	5.1-21.7	at ΔT= 270ºC
	TEG1 PB	Bi_2Te_3-PbTe	360	21.7	at ΔT= 320ºC
	PBTAGS series	PbTe-TAGS	600	1.3-30	at ΔT= 415ºC
	CMO series	Calcium/Manganese Oxide	800	12.3	at ΔT= 750ºC
	CMO Cascade	Calcium/Manganese Oxide with $BiTe_3$	600	11	at ΔT= 435ºC

1.5.2. Power output relation of TEG

The power produced from a TEG module is depended upon several parameters including temperature difference. In order to understand the governing factors that influence performance of a TEG, a representative section of a TEG module with two pairs of TE couples is shown in Fig. 1.4 [93].

The heat input and heat output in a TEG module at hot and cold side involve four components which can be associated with different energy carrier mechanism. The quantities for the hot side are (i) heat input (Q_H) from heat source, (ii) internal input owing to resistive heating (Q_{joule}), (iii) power output from thermoelectric effect (P_{TE}) and, (iv) heat output by conduction from hot side to the cold side (Q_{cond}). In the cold side the quantities are (i) heat output to cold source (Q_C), (ii) internal input owing to resistive heating (Q_{joule}), (iii) power input from thermoelectric effect (P_{TE}) and (iv) heat input through conduction from the hot side (Q_{cond}).

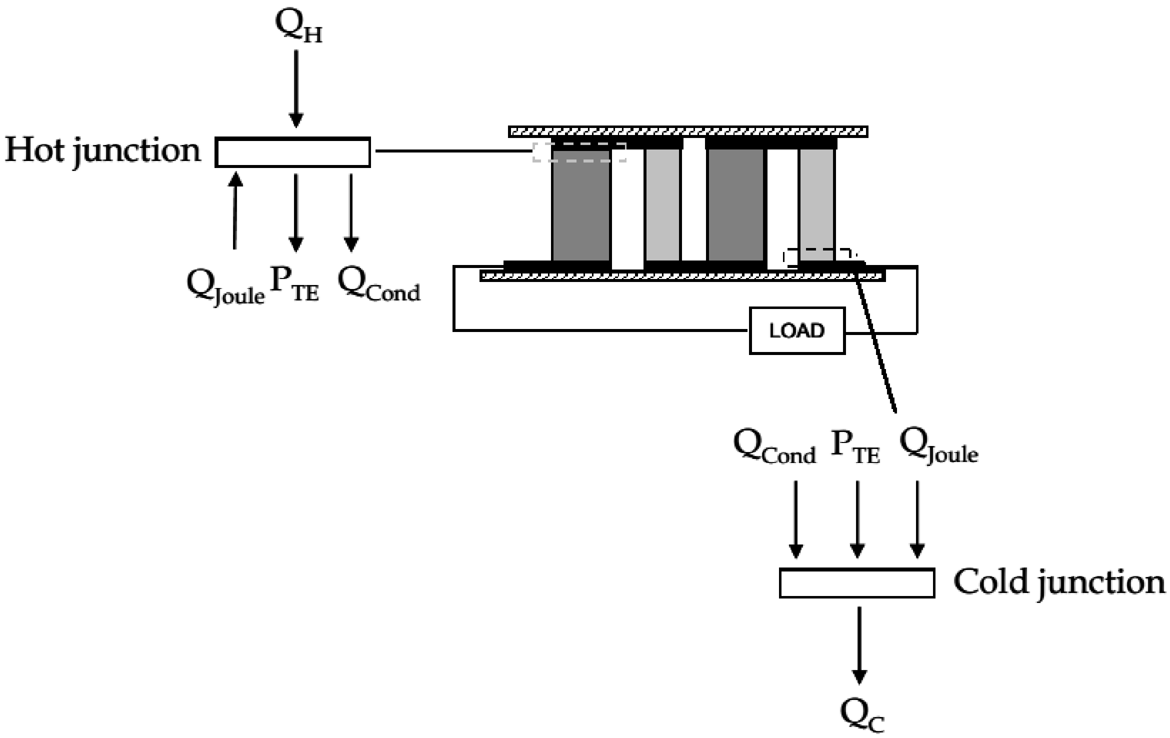

Fig. 1.4 Energy flow in a TEG module, Adapted from [93]

Thus the magnitude of heat input and output can be obtained from the following equations.

$$Q_{H_{TEG}} = P_{TE} + Q_{cond} - Q_{joule} \quad (1.3)$$

$$Q_{H_{TEG}} = (\propto IT_H) + K(T_H\text{-}T_C) - (0.5I^2R) \quad (1.4)$$

$$Q_{C\_TEG} = P_{TE} + Q_{cond} + Q_{joule} \quad (1.5)$$

$$Q_{C\_TEG} = (\propto IT_C) + K(T_H\text{-}T_C) + (0.5I^2R) \quad (1.6)$$

where $\propto$, I, T_H, K, T_C, R are the Seebeck coefficient, current output, hot side temperature, thermal conductance of the module, cold side temperature and internal resistance of TEG module, respectively.

When Eq. (1.6) is subtracted from (1.4), overall power output of the TEG module is obtained which is,

$$P_{TEG} = \ \propto I(T_H - T_C) - (I^2R) \quad (1.7)$$

Thus, it is observed that power output of a TEG module is directly affected by temperature difference. Higher the temperature difference greater is the power output. This signifies that the hot side temperature should be kept at a high temperature and the cold side temperature should be as low as possible.

1.6. Prospect of integration of TEG with biomass cook stove

Globally, TEG has been widely used in harvesting and converting heat from vehicular exhaust, industrial processes, geothermal energy, solar thermal and ocean thermal into electricity [84, 92, 94-99]. Thus, recovering heat as electricity from a biomass cook stove is technically possible.

There are several research that have reported the integration of TEG with biomass cook stove generating electricity in the range of 1-10W [49, 92, 100-110]. Typically TEG integrated biomass cook stove comprises of the biomass cook stove, TEG assembly and a load assembly. Part of the heat of combustion flows into the TEG assembly where it is converted into electricity. In the load assembly, the produced electricity is either stored in the battery or used to power electrical appliances.

TEG assembly is the most essential part of a TEG integrated cook stove which consist of a heat collecting unit, TEG module and a heat sink. TEG module is clamped between the heat collector and the heat sink. The hot side of the TEG attached to the heat collector is exposed to heat of combustion whereas the cold side of the TEG attached to the heat sink is maintained at a cold temperature. One of the important considerations for TEG assembly design is the maximization of temperature difference and selection of TEG module.

Several researchers have reported various design aspects of heat collector and heat sink in order to maximize temperature difference. Heat sink designs are based on type of convection (natural and forced), and cooling fluid (air and water). Since, power output is associated with temperature difference which is dependent on the design of heat sink, major advantage has been given to heat sink designs. It is reported that forced convection of cooling is able to achieve maximum temperature difference (~250ºC) compared to natural convection of cooling (~160ºC) across a TEG module. However, additional cost is required in terms of auxiliary power supply for forced convection mode of cooling. As long as power to drive forced convection is drawn from TEG, use of forced convection is a feasible solution.

Heat collector should be either high thermal conductivity metallic plate or metallic plate with extended surfaces. As discussed earlier, the temperature in the combustion chamber can reach as high as 600-800ºC, it is the role of heat collecting unit to receive, collect and deliver heat within the safe limit of TEG module. The thermal property (conductivity) and physical property (shape and strength to weight ratio) of selecting a heat collector material is an important aspect.

In addition to heat collector and heat sink design, selection of a suitable TEG module on the basis of thermal (peak hot side temperature), electrical parameters (voltage, current and output power) and economic parameter (cost/W) is equally important. Different types of TEG modules have its own ideal temperature range for effective conversion of heat to electricity. For stove based operation, TEG modules having a peak temperature limit of above 300ºC is ideal.

Since, TEG produces electricity on the basis of temperature difference, the voltage and current produced fluctuates with variation in temperature difference. It is obvious that temperature difference cannot be uniformly maintained across the TEG surface throughout the cooking operation owing to variation in firewood feeding. As a result, electronic management system to regulate voltage and current is used. The load assembly consists of electronic management system and different loads.

1.7. Prospect of integrating TEG with fixed clay biomass cook stove

All the research works related to TEG integrated biomass cook stoves are limited to portable biomass cook stoves. Research know-how generated is difficult to incorporate into a traditional fixed clay stove which is abundantly persistent in the majority of the rural areas of India. The thermo-physical (specific heat, thermal conductivity, thermal diffusivity and density) properties of fixed clay stove material are different to stove materials of different TEG integrated cook stove. As a result, heat transfer and heat loss inside the combustion chamber of a fixed clay cook stove will be significantly different. The assessment of heat loss and its recovery and conversion into electricity using TEG has not been carried out previously and needs attention.

The combustion chamber is susceptible to high fluctuating temperatures above 600ºC. However, integration of a TEG module within safety limit of 330ºC requires the understanding of the temperature distribution inside the combustion chamber. There are limited information of the identification of appropriate location for TEG mounting.

Field testing of a new technology is essential in order to understand technical limitations in conditions different to controlled laboratory environment [110, 111]. Not many researches on TEG integrated cook stove have been tested in field conditions except for a research work carried out in Malawi where TEG integrated cook stoves are deployed for 80 days. It is important to investigate user behavior on the performance of TEG integrated cook stove in terms of quality of fuel, cooking practice and usage of electricity.

The economic analysis of a technology is important in order to understand its applicability and adoptability. The price of TEG integrated cook stove developed in previous researches and also the commercialized are varying. With financial limitation of people residing in energy deprived area, the price acts as an added burden to them without proper financial institutions. In such a case, overall benefits a TEG integrated cook stove provides in terms of cost avoided from firewood savings, kerosene savings from facility of illumination and income generation from time saved in cooking should be investigated to address the applicability and adoptability of such a technology.

Eight of the 17 SDGs aim at improving the livelihood of deprived people by reducing poverty, hunger, improving health, equalizing gender, ensuring clean and affordable energy access, protection of the climate and protection of life on land. Development of TEG integrated cook stove must possess benefits to support SDGs so that it can be acceptable by the section of people living in energy deprived areas

In addition, policy for dissemination of TEG integrated cook stove is likely to provide insights in deployment of the technology to tackle the issues of lack of clean cooking and inadequate electricity access.

These analyses are absent in previous TEG integrated cook stove researches which are required to be addressed.

1.8. Objectives of the research

Based on the discussion above, the present Ph.D. research work is proposed with the following objectives

1. To develop a TEG system for recovery of waste heat as electricity from a fixed clay stove
2. To investigate the technical feasibility of TEG integrated fixed clay cook stove (TIFICS) in a typical rural area through field testing
3. To analyze the economic benefits and TIFICS promotion policy

1.9. Organization of the thesis

Following is the brief explanation of each chapter forming the thesis.

Chapter 1: Introduction

The subject of the thesis is presented in this Chapter highlighting the need of an urgent solution in cooking and electricity access, particularly in rural areas. Further, the potential of recovering, converting and delivering waste thermal energy into electricity from such cooking devices using thermoelectric generator (TEG) is discussed. The usefulness of generated electricity in a rural household in times of power outage is also discussed. Based on justification, objectives are formulated for the present work.

Chapter 2: Review of Literature

This Chapter presents a detailed review of potential of waste heat recovery using TEG in different applications. The key governing parameters for TEG performance in such applications are also discussed. Further, application of using TEG in recovering waste heat from biomass cook stove is presented in categorical manner in terms of design of heat collector, TEG module and heat sink. Finally a detailed review of economic analysis of technology distribution is presented.

Chapter 3: TEG integrated fixed clay stove

This Chapter presents the development of TEG assembly which is integrated with the fixed clay stove. Firstly, detailed analysis of waste heat estimation in the fixed clay stove is presented which is followed by development and assembly of the TEG system. Development of each component in the TEG assembly and its integration with the fixed clay stove are presented. Finally, the electrical performance testing of the TEG integrated fixed clay stove (TIFICS) at different test conditions are discussed aiming to confirm the technical feasibility of the technology.

Chapter 4: Field testing of TIFICS

The development of technology is targeted to benefit a typical set of rural population and basic characteristics of the population are biomass cooking, unreliable electricity, and low annual income which is considered as a desired test population. The field special features (viz., energy consumption in cooking and lighting, electricity demand, and cooking habit) required for understanding the applicability of the technology have been assessed through survey. The details of methodology, technology integration at user side, process of field testing, and field result analysis are presented in the Chapter. The field test is aimed to understand the issues concerning the field testing of TIFICS and feasibility of its usage by the target users.

Chapter 5: Economic benefits and TIFICS promotion policy

This Chapter discusses the economic analysis of TIFICS by means of investigating levelized cost of cooking, firewood savings and kerosene savings from the information gathered during the deployment phase of TIFICS. Further, the prospect of promotion of TIFICS through existing policy tools is also discussed.

Chapter 6: Summary and conclusions

This Chapter reviews the thesis's contents and presents a summary of overall findings and conclusions including new dimensions emerged from the work to address in future work.

The thesis end with Appendix and list of publications.

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