CHAPTER 4

Field testing of TIFICS

4.1. Introduction

Lack of access to clean cooking devices and electricity has become a serious concern worldwide. Accordingly, United Nations (UN) have set Sustainable Development Goals (SDGs) to make clean and affordable energy universally accessible which have been ratified by many national governments [1].

Integration of TEG with biomass cook stove as a means to utilize waste heat has been widely practiced with development of many commercial cook stoves. The results of technology development as well as its performance assessment are available [2-12]. The attempt of integration of TEG in fixed clay cook stove is limited. Cook stove is a technology of mass applications and user response is an important parameter which is required to be considered for design as well as to understand the acceptance and adoption of the cook stove. Limited researches are available concerning the field testing vis-à-vis on user perception of TEG integrated cook stove [9, 11, 12].

The development and performance testing of TIFICS was presented in Chapter 3 and based on its laboratory performance it was found to be a potential technology for mass applications in areas where there is limited access to electricity and which has affinity to fixed clay cook stove due to their food habit, customs and affordability.

In Assam (a north eastern state in India), more than 70% of the total population (~35 million) is still dependent on traditional fixed clay biomass cook stoves with efficiency less than 10% [13-15]. Moreover, several regions in remote rural villages face difficulties due to either lack of electricity access or unreliable electricity supply [16]. Government efforts are being made to disseminate improved cook stove, LPG cook stove and provide reliable electricity. However, the use of traditional fixed clay cook stove still persists and is expected to remain dominant till 2030 [17, 18].

Keeping in view of the above, it was attempted to deploy TIFICS in a typical rural area of Assam and analyse the user perception and response through a systematic study. Observations were recorded during a 90 day field testing. Data were also collected during pre-deployment phase and during deployment of TIFICS to understand changing pattern of energy resource usage by the user. The details of the methodology and results are presented in this Chapter.

4.2. Field testing procedure of TIFICS

The procedure for field testing is presented in the flowchart (Fig. 4.1). A rural area with solid fuel dominancy in traditional fixed clay biomass cook stove was selected for field testing of TIFICS. During the pre-deployment phase, a detailed techno-socio-economic household survey was conducted during September-December 2017 (Questionnaire attached in Appendix A) which was followed by the selection of households on the basis of a carefully designed criteria presented in section 4.5. TIFICS were installed with electrical and thermal parameter measuring devices. Each household was trained about the installation and data recording process of TIFICS. Field testing of TIFICS was undertaken after installation in order to obtain its usage, performance, and impact which are described below.

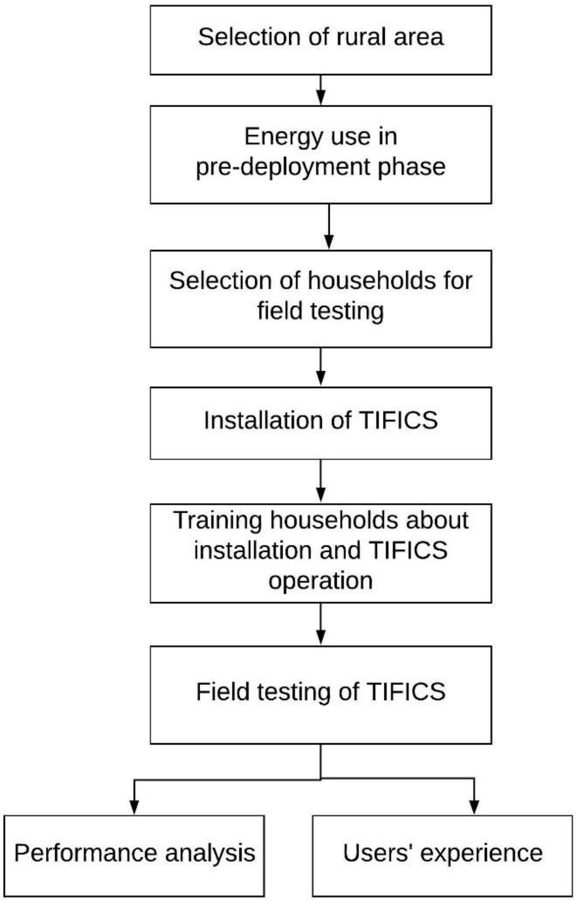


Fig. 4.1 Procedure of field testing of TIFICS

4.3. Selection of rural area

More than 90% of the total geographical area (78438 km^2) of Assam is rural and majority of households in rural area (~24 million) depend on biomass cooking [19]. Dikarijan, a village in the Chariduar subdivision of Sonitpur district in Assam was selected covering a geographical area of 2.64 km^2 with a population of 2598 [20]. All households of the village were not electrified probably either due to inability to afford or remoteness from nearby grid infrastructure. Further, the village was easily accessible from Tezpur University (25 km) (Fig. 4.2), which enabled daily monitoring of TIFICS. A brief profile of the village is shown in Table 4.1.

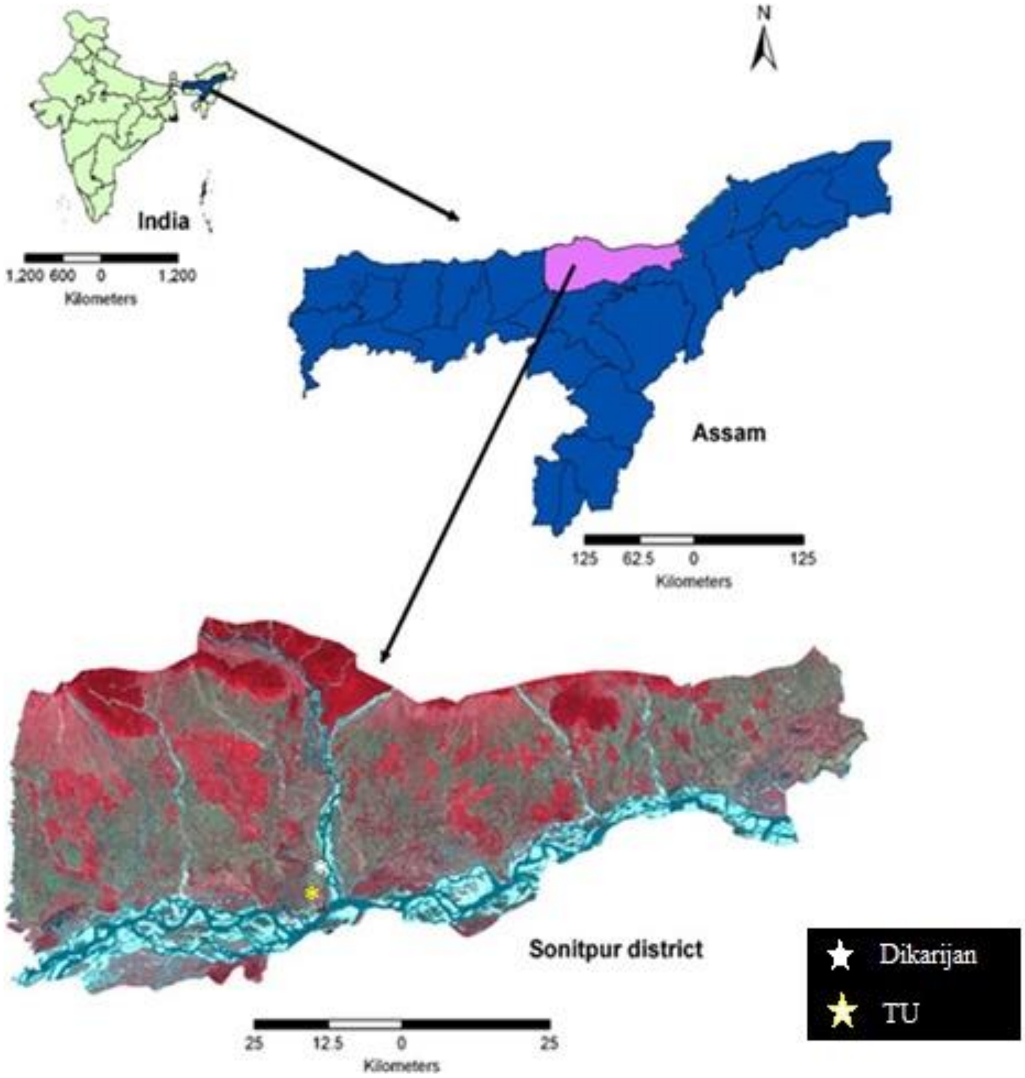


Fig. 4.2 Map showing the selected field area and Tezpur University (TU)

Table 4.1 Brief profile of DIkarijan village

Parameter	Value/description
Distance from TU	25 km
Total geographical area	2.648 km^2 (100% rural area)
Total population	2548
Male : Female	1.009
Major crop	Rice, Sugarcane, Jute
Major rural livelihood	paddy farming, livestock

4.4. Domestic energy use in cooking and lighting during pre-deployment phase

A survey was conducted in Dikarijan to determine the energy use and expenditure in cooking and lighting before deployment of TIFICS. A detailed format of questionnaire was prepared and face to face interview at each household was taken. The questionnaire included questions regarding basic information of households, energy consumption in cooking and lighting, economics (earning and expenditure on energy sources) and other information related to electricity supply, number of meals prepared, cooking time and time for firewood collection (Fig. 4.3).

In cooking, the consumption of LPG and firewood for a given duration (daily, weekly or monthly) was recorded from each household. Collected data was used to estimate annual per capita LPG consumption (MJ) and firewood consumption (MJ). For lighting, kerosene consumption on daily, monthly basis was recorded which was used to estimate annual per capita kerosene consumption (MJ). At households with electricity, the details of the accessories (power rating and duration of use) used by each household for lighting and entertainment (music player, TV, radio), communication (mobile), and other utilities (refrigerator, iron, oven) were recorded during the survey. Collected data was used to estimate the electricity consumption by the population at individual level i.e. per capita kWh.

There was a variation of firewood used among the households. The quantity of firewood data was converted into energy (MJ) considering uniform calorific value of firewood ignoring the marginal variations of the fuel type. Based on a similar study, average calorific value (16MJ/kg) of firewood was used to estimate energy use in cooking from firewood consumption [21]. Similarly standard calorific values of kerosene (36MJ/kg) and LPG (46MJ/kg) were considered [22].

Information related to health, expenditure pattern on energy sources, electricity available during the day, meals prepared, cooking time, time in firewood collection during pre-deployment phase were recorded.

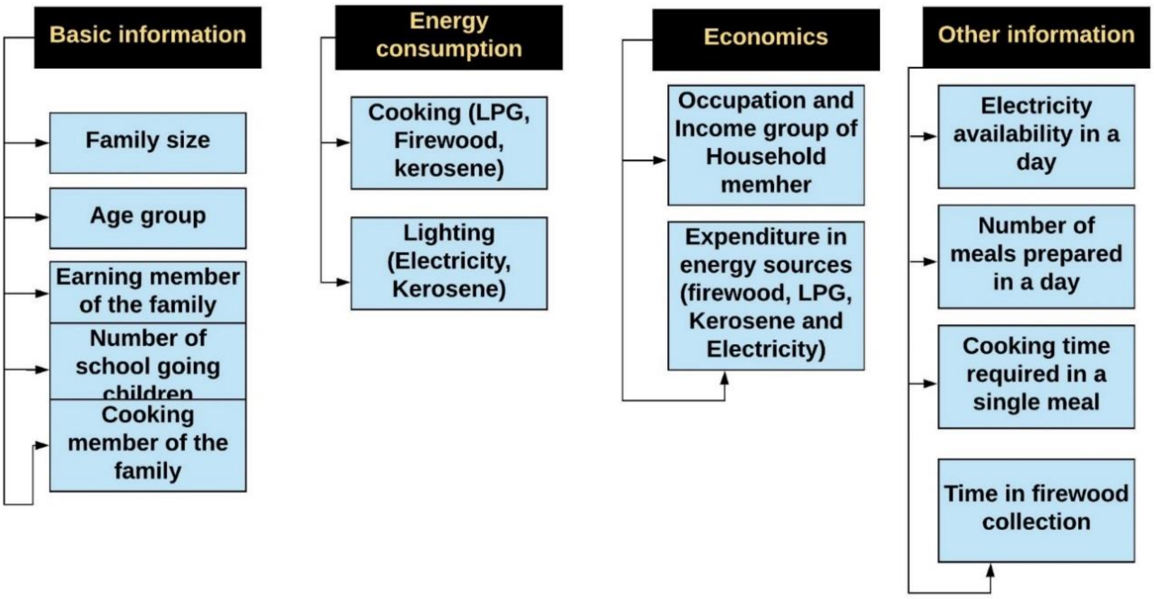


Fig. 4.3 Architecture for assessment of energy use in cooking and lighting

4.5. Criteria for selection of households

Based on the information generated from the survey, selection criteria framework was formulated to identify households for field testing. The criteria included the following:

- Have only traditional fixed clay stove for cooking
- No access to electricity and have a phone that they pay money to charge
- Need for substitute of kerosene
- Willingness to participate in field testing

Households fulfilling the above criteria were selected for deployment and field testing of TIFICS.

4.6. Installation of TIFICS and training of users

TIFICS were installed at the selected households following the procedure of stove construction (Appendix B). Users of selected households were trained during TIFICS installation which include stove material preparation and fabrication, assembling TEG components and integration of TEG assembly with the stove. Each TIFICS was equipped with temperature, voltage measuring devices and battery charging unit with a 3W LED bulb. Users were also trained about the procedure of utilizing electricity (viz., for illumination and mobile phone charging) from the battery. The consumption pattern of firewood and kerosene during deployment were recorded regularly.

4.7. TIFICS field testing

4.7.1. Battery charging circuitry

During laboratory tests, an average of 3.7h of continuous stove operation was required to fully charge the 3.2V 2.0 Ah Lithium Iron Phosphate ($LiFePO_4$) battery. A special battery charging circuitry was developed to accommodate the use pattern of the stove and possible use pattern of electrical appliances. This was done including the real information collected during the pre-deployment phase regarding usage of the stove and requirement of electricity. The circuitry as illustrated in Fig. 4.4 was developed to prevent battery discharge in the event of idle state of TIFICS.

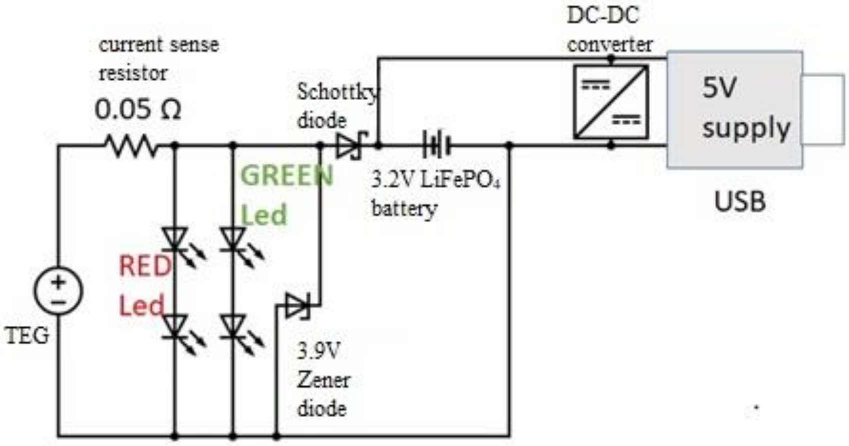


Fig. 4.4 Battery charging circuitry for illumination and appliance charging

Output voltage from the TIFICS during laboratory tests was found to vary between 3.19V and 4.03V (corresponding to temperature difference of 183ºC and 231ºC, respectively). A typical DC-DC converter circuit used by earlier researchers for similar purpose has been used [5, 7, 9-12]. A PFM controlled DC-DC converter (with a single male USB port) was used as voltage booster at the output of $LiFePO_4$ battery to charge a typical mobile phone battery requiring 5V of regulated supply and illuminate a 3W LED bulb during night time. A Zener diode (3.9V) was connected (Fig. 4.4) in parallel to the TEG module to prevent overcharging of battery by bypassing the battery upon full charge. A schottky diode was used to prevent the battery from discharging back to TEG when the TIFICS remained in an idle state.

4.7.2. Performance testing and devices used for data recording

Each TIFICS was equipped with three *K-type* thermocouples to measure hot and cold side of TEG and temperature inside the stove combustion chamber. The temperatures provided the stove usage information as well as calculation of temperature difference across the TEG. Two digital multimeter were used to record the voltage output of TEG module and voltage drop across the sense resistor (0.05Ω) in the battery charging circuit. The voltage drop across the sense resistor was used to calculate the current flowing through the circuit. Power production by the TEG was estimated from TEG output voltage and the current and its variation with respect to temperature difference was investigated. Electrical energy generated (Wh) was determined from power-time curve of TIFICS operation. Finally cumulative electrical energy generated after 90 days of field testing was estimated.

Power consumption by users through light illumination and mobile phone charging was investigated. A USB power meter was connected at the output of USB 5V supply port. The power meter measures real time load voltage and current consumed from the USB which was converted into power. Cumulative electrical energy consumption was estimated after 90 days of field testing.

The specification of the measuring devices used for temperature and voltage recording is shown in Table 4.2.

Table 4.2 Measuring devices

Equipment	Specifications
K-type thermocouple	Temperature range: -50ºC to 1300ºC, Accuracy: ± 0.3% of rdg + 1ºC (-50ºC to 1000ºC) and ± 0.5% of rdg + 1ºC (1000ºC to 1300ºC).
Multimeter	Multimeter: DC voltage range: 200mV to 200V, Accuracy: ± 0.5% of rdg + 1 digit, Resolution: 100µV-100mV, DC current range: 200µA-20A, Accuracy: ± 0.8% of rdg + 1 digit, Resolution: 0.1µA-10mA.
USB Power meter	Voltage measuring range: 3.5~7V (V), Input voltage: 3.5~7V, Output voltage: 3.5~7V, Ambient temperature: 0~60ºC. Also measure the operating current (0-2.5A) of the output voltage of the USB port. Resolution: Voltage 10mV, Current 1mA, Error voltage <±1%, current <±2%,

4.7.3. Firewood characterization

Every household used different type of firewood to carry out cooing activities. Characteristics of firewood (proximate analysis and calorific value) have an influence on the performance of TIFICS. Therefore, to understand this relationship, detailed characteristics of firewood at selected households had been completed.

Firewood samples were collected as received basis during the TIFICS deployment phase and the proximate analysis (moisture content, volatile matter, ash content and fixed carbon) and calorific value were investigated.

The moisture content was determined from the received sample as per the ASTM-D 4442 standard [23]. The received samples were oven dried, ground and sieved into powder bearing a particle size of 0.250μm. The volatile matter and ash content of the ground samples were determined as per ASTM-E 872 and ASTM-E 1755 methods, respectively [24, 25].

The calorific value of firewood was obtained from the ground samples using an adiabatic bomb calorimeter as per the ASTM-E 711 method [26].

4.8. Impact analysis of TIFICS

Kerosene was predominantly used for illumination and one of the major aspects of TIFICS is to prevent use of kerosene. For cooking, night time illumination was required. The user response and subsequently its potential on this aspect was analysed from the result of the study. It was expected that the investigation would result in health benefit.

Extensive use of TIFICS replacing the traditional cook stove due to the additional benefit for electricity generation would also result in reduction of indoor air pollution owing to provision of chimney. The benefit that was being obtained for using TIFICS was also analysed from the experience of the users.

TIFICS was expected to provide additional benefits which are (i) provision of an auxiliary electrical source in a non-electrified household for charging battery powered devices, (ii) reduction of firewood consumption, and (iii) provision of hot water.

According to several reports [27-29], cooking time and comfort in cooking are important social factors that affect the choice of cook stove. The experiences of using TIFICS in terms of ease in cooking, time saved in cooking, illumination in cooking space, provision of hot water during cooking and comfort during study hours for children were used to analyse the potential impact of TIFICS.

Introduction of a new technology is mostly associated with some changes of the system.

For e.g. in case of an improved cook stove, the type and the related practices of collection and preparation of a fuel are associated. Prospect of acceptability of a new stove increases if the fuel compatibility issues are addressed. In the current context, this is also being analysed and discussed.

In view with this discussion, the experiences of using TIFICS by household in terms of the above mentioned issues was analysed and discussed.

4.9. Results and Discussion

4.9.1. Domestic energy use pattern in Dikarijan village

As mentioned in the previous chapters, an attempt to introduce TEG integrated fixed clay stove has been made. The present research work presents the development of the technology considering the different parameters of the population targeting wider acceptance. Also, it is expected that the electricity generated utilizing the waste heat from the cook stove would be useful considering the present level of energy consumption in the selected rural area. More particularly, the non-availability of electricity causes difficulties due to poor lighting condition as well as hardship related to harmful kerosene. Further, almost all the households in the selected area use the traditional cook stove. Introduction of TIFICS is expected to replace the traditional cook stove thereby giving all the benefits of an improved cook stove of saving fuel, clean environment during cooking in addition to generating electricity for illumination and mobile charging. Though general trend of energy use pattern is known, it is desired that understanding and the knowledge on the specific use pattern in the selected area would help us to understand the possible and probable impact of the technology which further would help us to transfer the technology covering a wider area. Therefore, detailed survey has been conducted as discussed in the methodology. Results of energy use pattern during the pre-deployment and after deployment of TIFICS has been presented below.

A total of 93 households were surveyed in Dikarijan in Sonitpur district. The population statistics and economic profile as recorded during the study are presented in Table 4.3. Majority of population (226) are in the working age category i.e. 18-60 years. Whereas, 194 people fell in the category of school going children (5-13 years) and teenagers (13-18 years).

Table 4.3 Population statistics of the selected rural cluster

Particulars	Group	Number
Number of family members, age (years) group wise	Below 5	30
	5-13	101
	13-18	93
	18-60	226
	Above 60	59
	Total population	509
Annual Income group (households)	<1500US$	90
	1500-3000US$	1
	>3000US$	2
	Total Households	93

There is a disparity of annual household income which effects their level of energy consumption About 90 out of 93 households earn less than 1500US$ which is even less than the average national per capita income (1820US$) [35, 36]. Only a single household earn more than 3000US$ per annum.

Table 4.4 presents the energy consumption status of Dikarijan in cooking. There are two categories of fuel users in cooking viz. single fuel user and dual fuel user. Users of single fuel use either firewood (F) or LPG (L) whereas dual fuel users cook with both firewood and LPG.

Firewood is the most predominant fuel in Dikarijan village. Around 76% of the households used solely firewood in cooking whereas only one household used LPG entirely as their cooking fuel. Overall, almost all households (99%) used traditional cook stove (Fig. 4.5) with variation in their design with similar disadvantageous feature of indoor air pollution as reported by users. Around 24% of the households used duel fuel.

Annual per capita energy consumption (14344MJ/capita/annum) using solely firewood is higher compared to dual fuel users (11869MJ/capita/annum) and sole LPG user (2556MJ/capita/annum). Efficiency of cooking devices is related to energy consumption which is clearly noticeable from the variation of energy consumption in fuel users. The lower efficiency traditional cook stove of only firewood users consumes more energy as compared to other category of fuel users.

Affordability of LPG at 13US$/cylinder is an issue whereas purchasing firewood at 0.07US$/kg on a daily or weekly basis and in some cases collected from homestead is convenient. Further, most of the household are accustomed in cooking with traditional cook stove. Considering all these reasons, although all the government initiatives to distribute LPG stoves, there will be a period where firewood cook stove will still remain predominant.

Overall in the village, an average of 408 tonnes of firewood were used in cooking annually which amounted to be equivalent of 6533 GJ of energy. Based on the current population, annual average per capita firewood consumption is 2.35kg/capita/day (37.6MJ/capita/day). The level of firewood consumption was also earlier reported in villages of Jorhat, India (2.16 kg/capita/day), northeast Indian hilly regions (3.1 kg/capaita/day) and Gariwal Himalayan region in India (2.52 kg/capita/day) [26-28]. The variation in quantity of consumption is due to differences in fuel characteristics, climatic conditions, differences in practices in cooking and type of cook stove.

Table 4.4 Energy consumption in cooking

MJ/capita/annum	Dual fuel	Single fuel	
	L+F	F	L
Average	11869 (21)	14344 (71)	2556 (1)
Maximum	17005	21413	2556
Minimum	6885	7397	2556
Standard deviation	2898	3285	0

L+F: LPG and Firewood, F: firewood, L: LPG

Values in parenthesis are number of households

Fig. 4.5 Fixed clay made biomass cook stoves with design variations in Dikarijan

The dominancy of firewood consumption justifies the requirement of an improvement of the existing devices so that issues related to health, energy saving and environment can be addressed.

There was a variation of household electrification in the village. Table 4.5 illustrates the annual electricity consumption in Dikarijan village. Around 30% (28 household) of total households lacked electricity access. The maximum annual per capita electricity consumption was estimated to be 273kWh whereas the average per capita consumption was 122kWh which is lesser compared to Assam (339 kWh) and India (1122 kWh) [16]. All electrified households have reported the condition of unreliable electricity supply of grid electricity with 3-4 h/day of unscheduled load shedding during peak demand. According to Assam Power Distribution Limited, Assam, India, the power cuts or load shedding was owing to the state's fragile grid infrastructure, however efforts were being made to improve grid electricity supply and reduce load shedding [37].

Kerosene was used by every household, particularly for space lighting (Table 4.5). The maximum annual per capita kerosene consumption was 725MJ whereas the average per capita consumption is 325MJ. Every non-electrified household in the village used more than 40L/annum of kerosene for space lighting whereas for electrified household, the annual consumption was between 24-36L.

Every household purchased 3L of kerosene at subsidized rate of 0.36US$ per litre in a month. Frequent load shedding forced electrified users to depend on kerosene lighting and majority of school going children had to face hazardous impact of fumes from kerosene lamps.

Another noticeable feature observed in the village was the penetration of mobile phone communication. Almost every non-electrified households owning mobile phone paid around 0.15US$ to charge their mobile phone which can be compared to several study in India and some countries of Sub Saharan Africa where users pay a certain sum of money to charge their battery powered devices [40].

Overall, due to the dominancy of traditional fuel in their energy mix, the rural clusters were not benefited in terms of its services. Indoor air pollution was one of the primary issues reported by the respondents with the firewood based cooking. Access to LPG was considered better means of living and therefore, it was every ones aspiration. However, supply uncertainty, remoteness from the mainland and its non-affordable capital cost have been the major limitations against LPG usages. Unreliable electricity supply forcing users to switch to kerosene lighting was often a discomfort. Overall, non-availability of electricity, difficulty of obtaining LPG and hazardous kerosene result discomfort for the people living in Dikarijan despite of consuming higher share of total end-use energy.

Table 4.5 Annual energy use lighting (energy/capita)

Energy	Range	Average
Electricity, kWh/capita	54-275	122 (70%)
Kerosene, MJ/capita	108-720	325 (100%)

Value in the parenthesis indicate % share of total household

4.9.2. Selection of households and installation of TIFICS

Based on the criteria in Section 4.5, five households (denoted by H1, H2, H3, H4 and H5) were selected. TIFICS equipped with temperature and voltage measuring devices along with battery charger and LED bulb were installed. The installation of the IIFICS is shown in Fig. 4.6.

Fig. 4.6 TIFICS installation at selected households

4.9.3. TIFICS field test: stove usage

The detailed schedule of TIFICS testing at selected households is shown in Table 4.6. The first test began at H2 on 29 December, 2017. Simultaneously, field tests at H1, H3, H5 and H4 began on the dates as shown in Table 4.6. TIFICS at H1 and H5 failed after operating for 12 and 2 days of field testing, respectively and TIFICS at H2 failed after 54th day of operation. The TEG assembly of TIFICS at H1 was dislocated during fuel feeding and the TEG module at H2 faced thermal stress leading to electrical failure. The detailed discussion on these issues is discussed in Section 4.10. However, new TIFICS were installed at H1 and H2 and field testing was continued which were still in operation even after the 90 days testing period. Lack of awareness of the TIFICS and increased affinity towards the existing traditional cook stove had led H5 to operate TIFICS only for two days. As a result, limited information at H~~2~~ could be generated. The following section includes the information obtained from field tests.

More than 400h of TIFICS operation was recorded at each household except H5. H2 operated TIFICS for a total of 449h in 90 days which was the maximum among other household.

Table 4.6 Schedule of TIFICS field experiments at households

Household	Start date	End date	Number of days	Number of meals prepared using TIFICS	Maximum usage, h/day (total hours)
H1	10-01-2018	15-07-2018	90	236	6 (412)
H2	29-12-2017	27-05-2018		246	6 (449)
H3	21-01-2018	21-04-2018		253	6 (441)
H4	20-03-2018	20-06-2018		223	7 (431)
H5	22-01-2018	24-01-2018	2	6	3 (8)

Values inside parenthesis are total TIFICS usage hours

4.9.4. TIFICS performance

There was a variation in the achievable peak temperature difference and power production at each household. The variation of average temperature difference at each household is plotted against time of stove operation in Fig. 4.7. H2 achieved a peak temperature difference of 255ºC which was higher than laboratory tests (231.2ºC). Whereas, H1, H3 and H4 achieved a peak temperature difference of 221.8ºC, 216ºC and 209ºC, respectively. Several reasons were identified which attributed on the higher temperature difference achieved at H2.

The temperature difference depends on the hot side temperature and the cold side temperature of TEG module. The hot side temperature is governed by the temperature inside the combustion chamber which depends on the properties of fuel. The average hot side temperature achieved at each household is plotted against time in Fig. 4.8 and Table 4.7 presents the fuel characteristics of firewood used at each household. H2 achieved the maximum average hot side temperature (320°C) compared to laboratory (301°C), H1 (297°C), H3 (296°C) and H4 (291°C). The calorific value (CV) of firewood used at H2 was higher than the CV of firewood used in laboratory tests. However, firewood characteristics at H1, H3 and H4 were inferior to firewood used in laboratory tests. The moisture content and ash content of firewood used at H3 and H4 was higher compared to laboratory test conditions. Whereas, the moisture content was maintained during laboratory tests was 6%. Further, owing to higher ash content of firewood at H3 and H4, thick layer of ash deposition on heat collector plate at H3 and H4 was observed (Fig. 4.9) after the completion of field tests. The formation of ash deposition on heat collector plate had limited the maximum achievable hot side temperature during the later stages of field testing and thus the achievable temperature difference. Further, during laboratory tests, we have maintained a fuel feeding rate of 16.67 gm/min (i.e. 100gm/6min) according to standard defined in Bureau of Indian standard for cook stove testing [38]. However, users fed firewood as per their own intuition and this was also one reason for achieving lower temperature difference across TEG module at H1, H3 and H4.

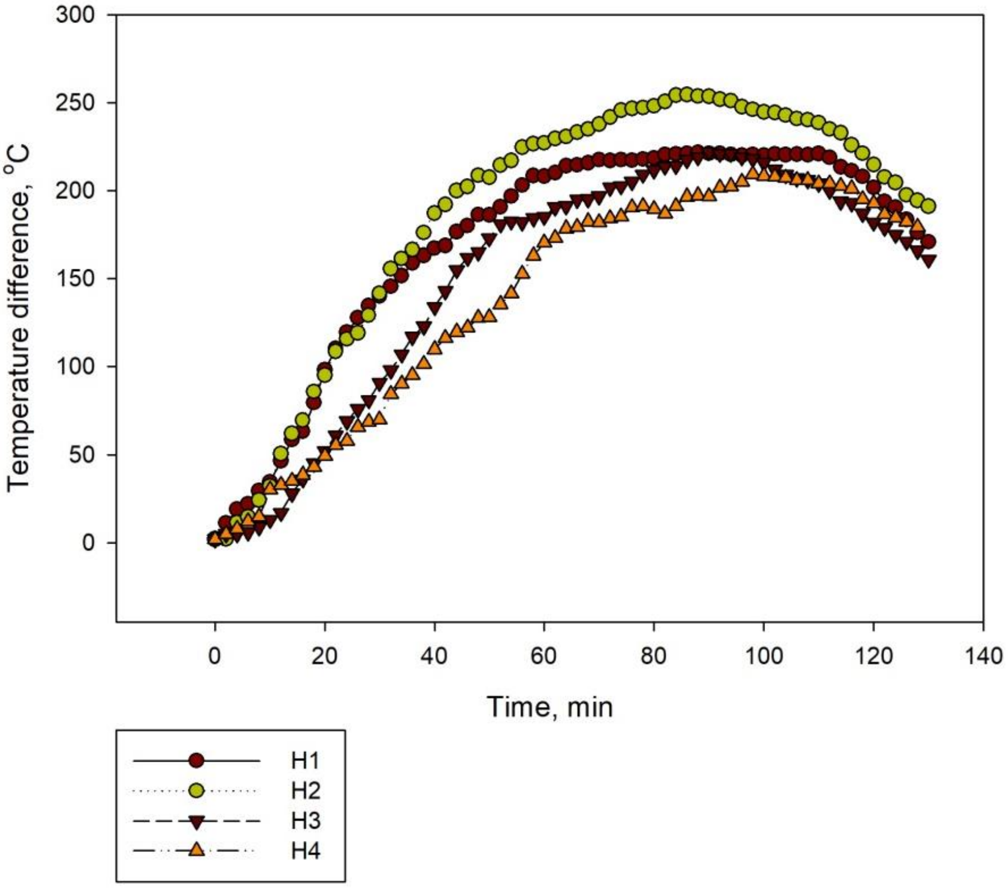


Fig. 4.7 Variation of Temperature difference across TEG module at each household

Table 4.7 Physical and fuel property of feedstock collected from households

Feedstock	Moisture content, %	Volatile matter, %	Ash Content, %	Fixed Carbon, %	CV, MJ/kg
H1	14.45	78.84	5.14	16.05	17.87
H2	12.83	80.84	3.74	15.42	18.28
H3	21.42	64.46	10.46	25.08	15.05
H4	28.41	71.51	11.29	17.20	14.64

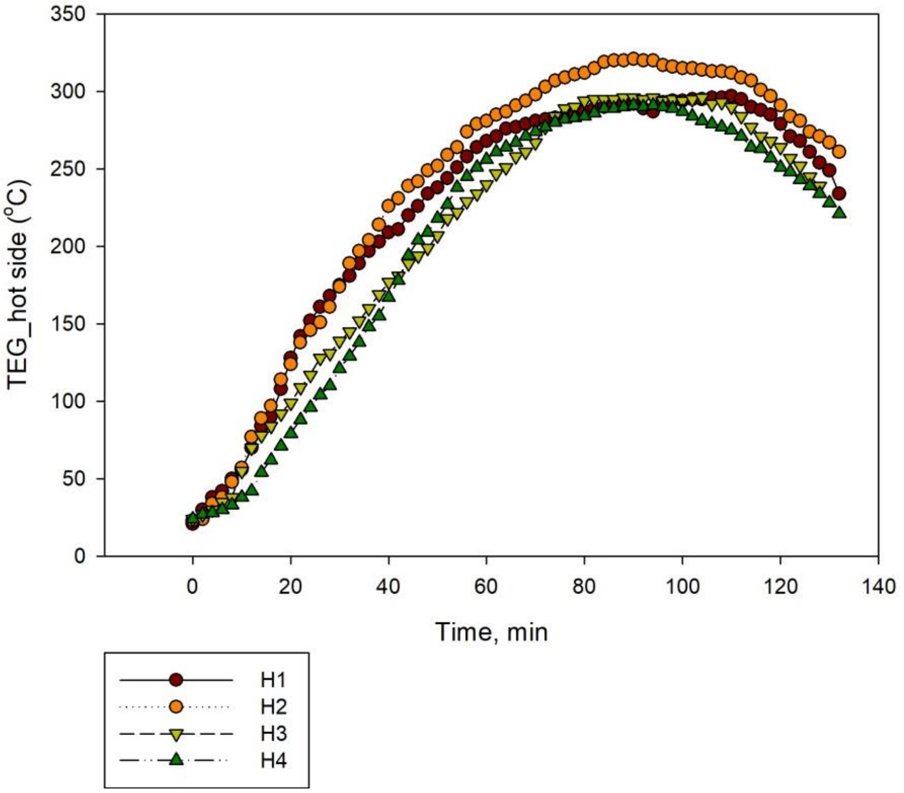


Fig. 4.8 TEG hot side temperature at each household during TIFICS operation

Ambient temperature determines the cooling capacity of the heat sink attached to the cold side of the TEG module. The peak cold side temperature achieved at H1, H3 and H4 was in the range of 73-74ºC whereas it was 69ºC in H2. Since, the study was conducted from winter (December—February) to summer (June-July), there was a variation in ambient temperature (19-30ºC). Majority of the testing at H2 was conducted during January to February where the ambient temperature was in the range of 19-22ºC. TIFICS at H1 was also operated for 12 days prior to failure during winter but it was reinstalled during the beginning of March, where the ambient temperature varied from 25 to 28ºC.

Fig. 4.9 Ash deposition on heat collector plate at H4

The variation of power production, voltage and current with respect to temperature difference are plotted in Fig. 4.10, 4.11, 4.12, and 4.13 for H1, H2, H3 and H4, respectively. The fundamental thermoelectric principle of thermoelectricity was justified as a linear relationship between power production and temperature difference was observed at each household. Owing to higher temperature difference (255°C) achieved at H2, the power production was also higher (3.2W) compared to H1 (2.6W), H3 (2.4W) and H4 (2.3W), respectively. The variation of low power production at H1, H3 and H4 was identified to be attributed to high cold side temperature, cooking practice and fuel characteristics. There was controlled conditions during laboratory tests (i.e. specific fuel sizes, uniform fuel feeding rate and prevention of ash and charcoal build up in CC) for which the temperature profile of CC and TEG hot side was without much fluctuations. However such controlled conditions were absent owing to the presence of numerous household activities of user during TIFICS usage for which the CC and TEG hot side temperature fluctuated noticeably.

The variation of TEG voltage with time at H1, H2, H3 and H4 from Fig. 4.10, 4.11, 4.12, and 4.13 indicates the quality of voltage that was being generated to charge the battery. Typically, the battery required a threshold voltage of 3.2V to charge and DC-DC convertor USB socket connected to the battery required at least 0.9V to step up to 5V for operating LED light and charge mobile phone. About 160ºC of temperature difference was required for the TEGs to obtain 3.2V or higher voltage. As long as TIFICS was operated and temperature difference above 160ºC was maintained, the battery received the sufficient voltage to charge. It is observed from Fig. 4.7 that temperature difference above 160ºC was achieved for majority of time during TIFICS operation.

Further, it is important to mention that, H2 produced peak electrical power of more than 3W from 47th to 54th day of field testing. The reason identified was the higher TEG hot side temperature that exceeded the maximum TEG hot side temperature obtained in laboratory tests of 301.2ºC. The variation was identified due to the change in calorific value of fuel type used (Table 4.7). During this duration (47th day to 54th day), the TEG hot side temperature on different operational hours exceeded the threshold limit of 330ºC (Fig. 4.14). On 54th day, TIFICS at H2 failed to produce electrical power. When inspected, it was observed that the TEG module at H2 exhibited failure owing to thermal stress as the p-n couples inside the TEG module are disconnected from the solder joints.

The variation of average power produced at each household against time of TIFICS operation is plotted in Fig. 4.15. Overall three meals were prepared using TIFICS i.e. breakfast, lunch and dinner. During the TIFICS deployment phase, breakfast preparation started between 6 and 7AM, lunch between 11AM and 12 noon and dinner between 7 and 8PM. TIFICS was observed to be at cold phase before each operation, Hence, a transient power generation was observed in each household. However, production of power increased after about 20 min of TIFICS operation. Overall, TIFICS was observed to be operated for more than 1.5h to prepare a meal. As mentioned in previous reports [9, 11, 12], the electrical energy generation of each household was determined by integrating the power curve mathematically as depicted in Fig. 4.15. H2 generated an electrical energy of 1.8Wh which is higher compared to H1 (1.2Wh). H3 (1.18Wh) and H4 (1.01Wh). As discussed earlier, the power generation of H3 and H4 was dictated by lower hot side temperature, temperature difference, fuel characteristics and cooking behaviour, electrical energy generation was also lower in H3 and H4.

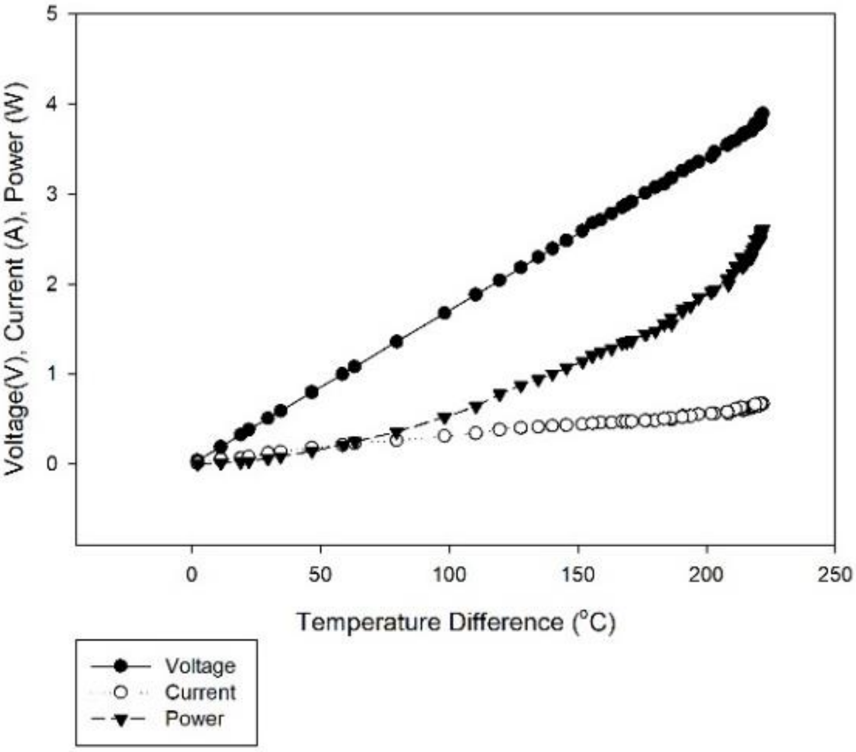


Fig. 4.10 Variation of voltage, current and power with temperature difference at H1

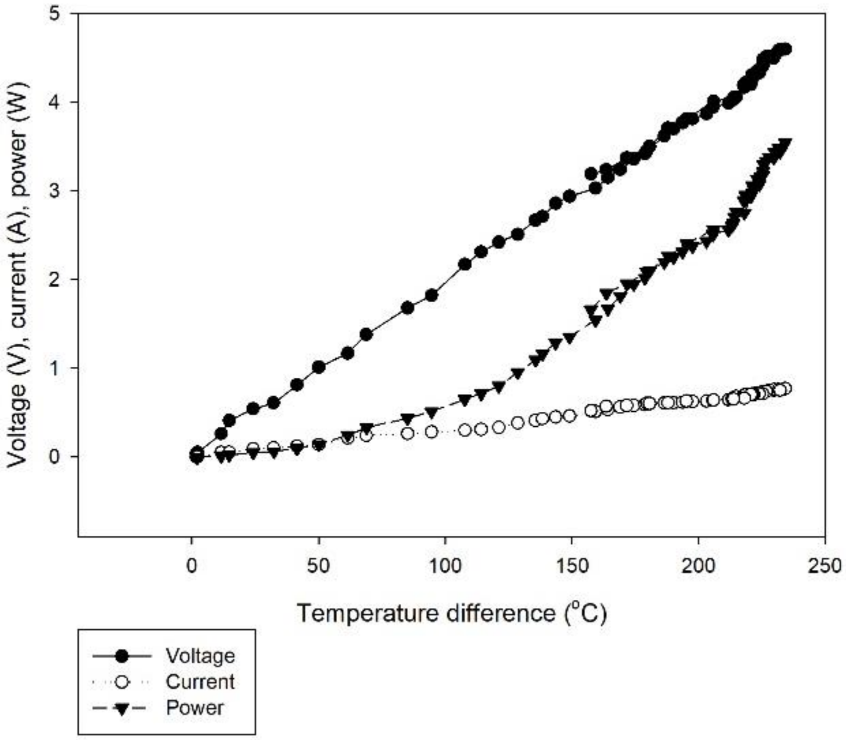


Fig. 4.11 Variation of voltage, current and power with temperature difference at H2

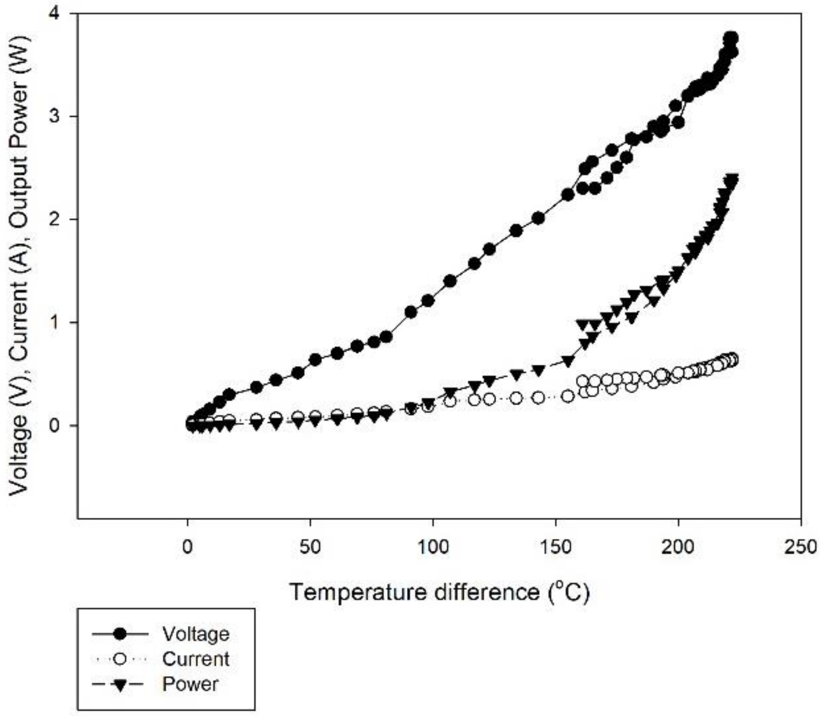


Fig. 4.12 Variation of voltage, current and power with temperature difference at H3

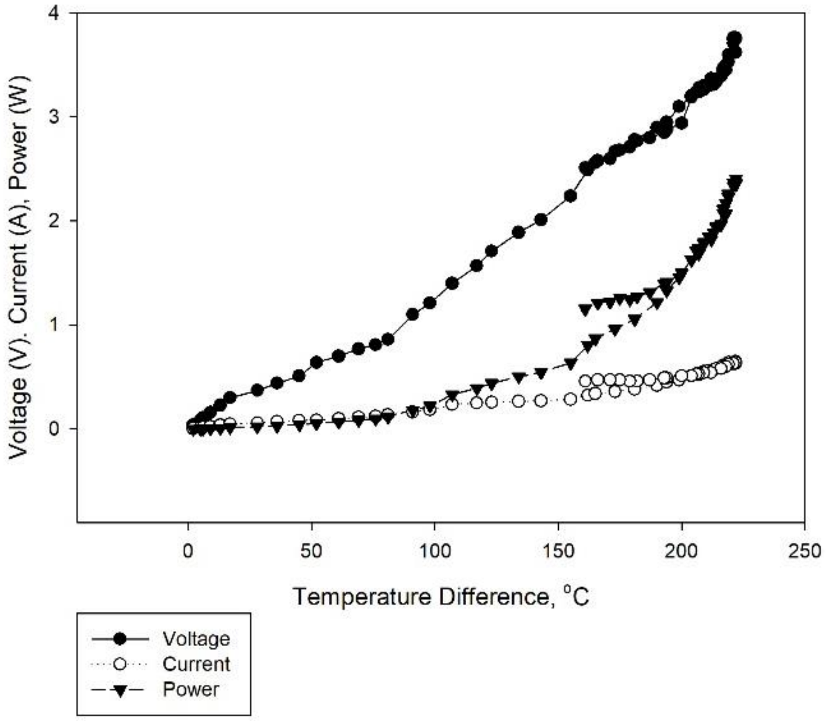


Fig. 4.13 Variation of voltage, current and power with temperature difference at H4

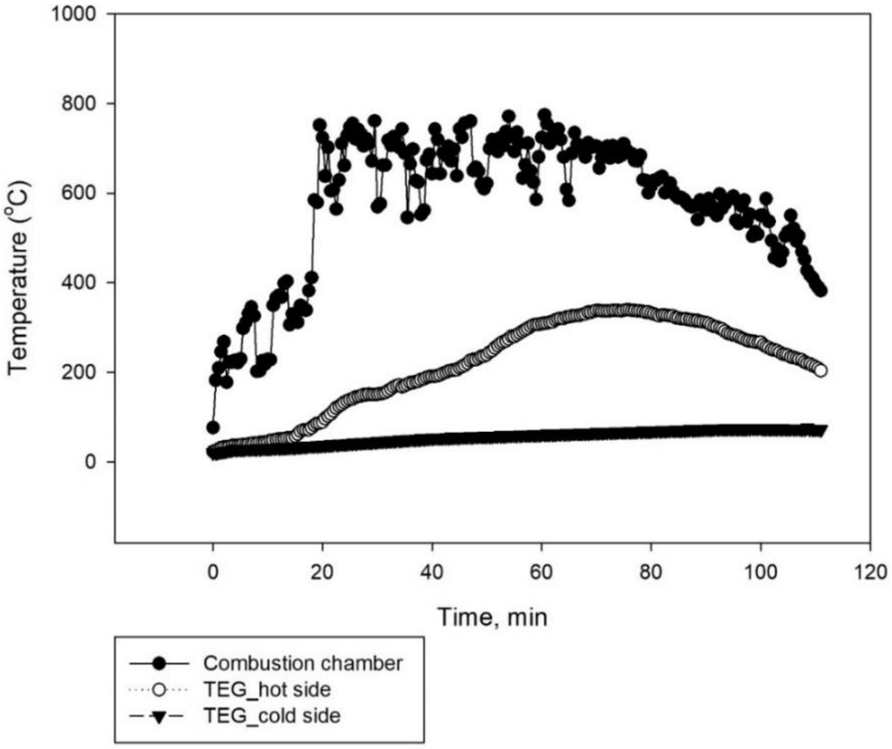


Fig. 4. 14 Ttemperature of TEG assembly from 13/2/2018 (47th day) to 20/2/2018 (54th day) of TIFICS at H2

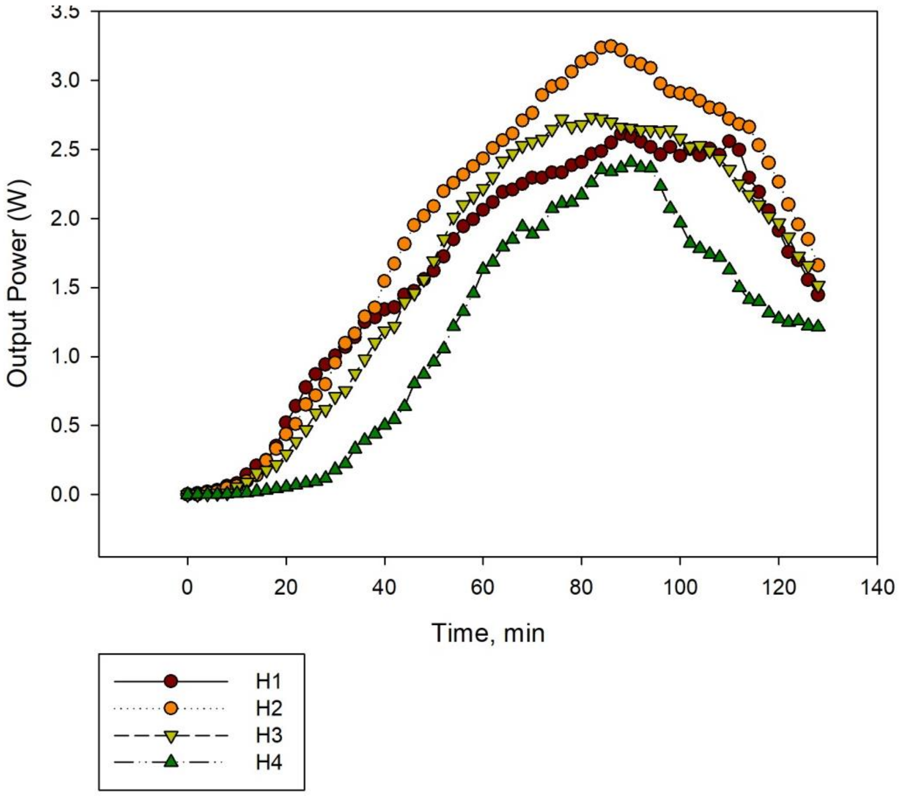


Fig. 4.15 Variation of power at each household during TIFICS operation

4.9.5. Electrical energy supply and demand

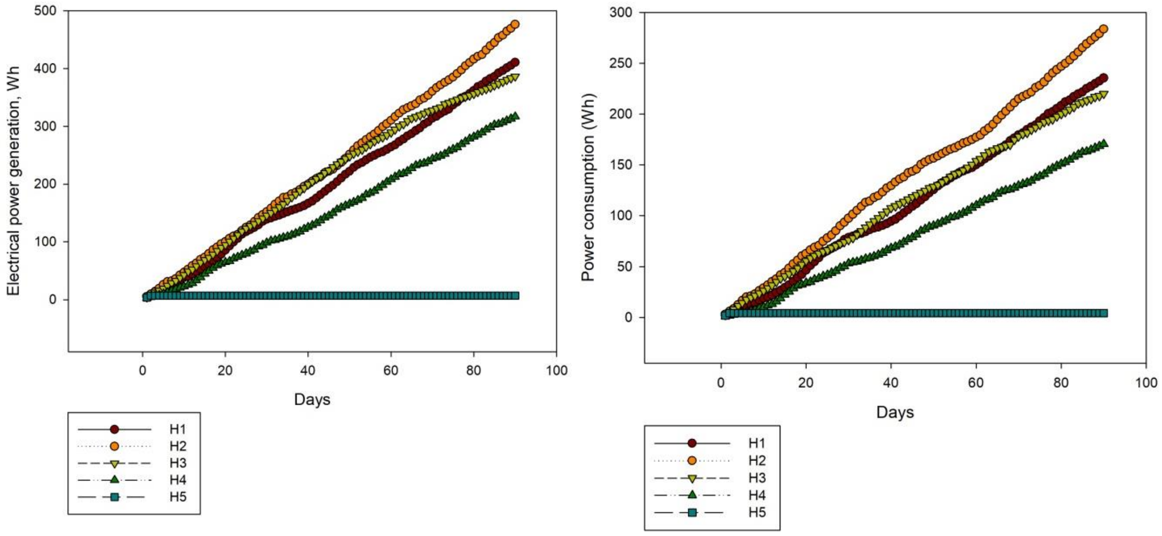
Cumulative electrical energy produced and consumed at each household is plotted in Fig 4.16 (a) and 4.16(b), respectively for the entire duration of the field study. From Fig 4.16 (a), it is observed that the energy curve is fairly linear with duration of field testing for households H1, H2. H3 and H4 which means that daily electrical energy generation was reasonably constant and TIFICS usage was consistent over the duration. However, flat line can be seen in case of H5 after two days of operation which is evidence of the fact that TIFICS was used only for two days.

TIFICS at H2 produced the maximum (476Wh) electrical energy followed by H1 (410Wh), H3 (386Wh), H4 (317Wh) and H5 (7Wh). Even if, each of the TIFICS was operated for more than 220 times (Table 4.5), the performance of TIFICS at H2 was better as it produced more power (3.2W) and electrical energy (1.8Wh) compared to the other TIFICS. The same observation can be said for overall electrical energy consumption.

H4 produced only 317Wh in the entire duration of field test. When compared to H2, TIFICS at H4 produced lower power (2.3W) and electrical energy (1.01Wh) for which overall power production was low. As mentioned in the previous section, the reason for lower power production is pertinent to lower temperature difference which was caused by ash deposition on the heat collector plate as shown in Fig. 4.9.

Similar field test of TEG integrated cook stove in Malawi reported around 700Wh of electricity production over duration of 80 days where the stoves were used about 230 times with 8h/day usage on average [9, 11, 12].

The electrical energy produced was stored in the 3.2 V $LiFePO_4$ batteries. The end use was LED illumination and mobile phone charging. Every household owned a standard keypad mobile phone with standby time of more than 3 days. The cumulative electrical energy consumed from the end use is plotted for the entire duration of the field test in Fig. 4.16(b).



(a) (b)

Fig. 4.16. Electrical energy supply and demand (a) Cumulative electrical energy generation, (b) Cumulative electrical energy consumption

A 3W LED bulb was used which was connected for most of the time at the outlet of the USB socket. User disconnected the LED bulb when they wanted to charge their mobile phone. H2 consumed about 285.5Wh of electrical energy through lighting and phone charging. Majority of energy consumption (227Wh) was attributed to illumination whereas only 58.5Wh was attributed to phone charging. It is important to note that in most cases, the phone was charged when TIFICS was not in operation. Occasionally the phone was charged during stove operation. The power produced was sufficient to provide 3h of illumination in the cooking space and in some cases benefited in studying purpose for school going children. During every occasion in night, LED would remain illuminated when TIFICS was still in operation in which case the battery was getting charged and discharged at the same time.

The cumulative electrical energy consumed at H1, H3 and H4 was estimated as 235.5Wh, 195Wh and 170Wh, respectively. At H1, energy consumption of 178.5Wh was thorough lighting whereas 57Wh was through mobile phone charging. In H3, 2h of night time illumination was obtained from TIFICS which contributed to 67% (131Wh) of energy consumption whereas the rest was attributed to mobile phone charging. All of the electrical energy consumed in H4 was attributed to lighting as shown in Fig 4.17(b). It was learnt that the mobile phone was out of order at H4. Similar to H2, the LED was kept illuminated when TIFICS was in operation during night at all the other households.

In such a situation, there was a possibility that insufficient power generated is stored in the battery.

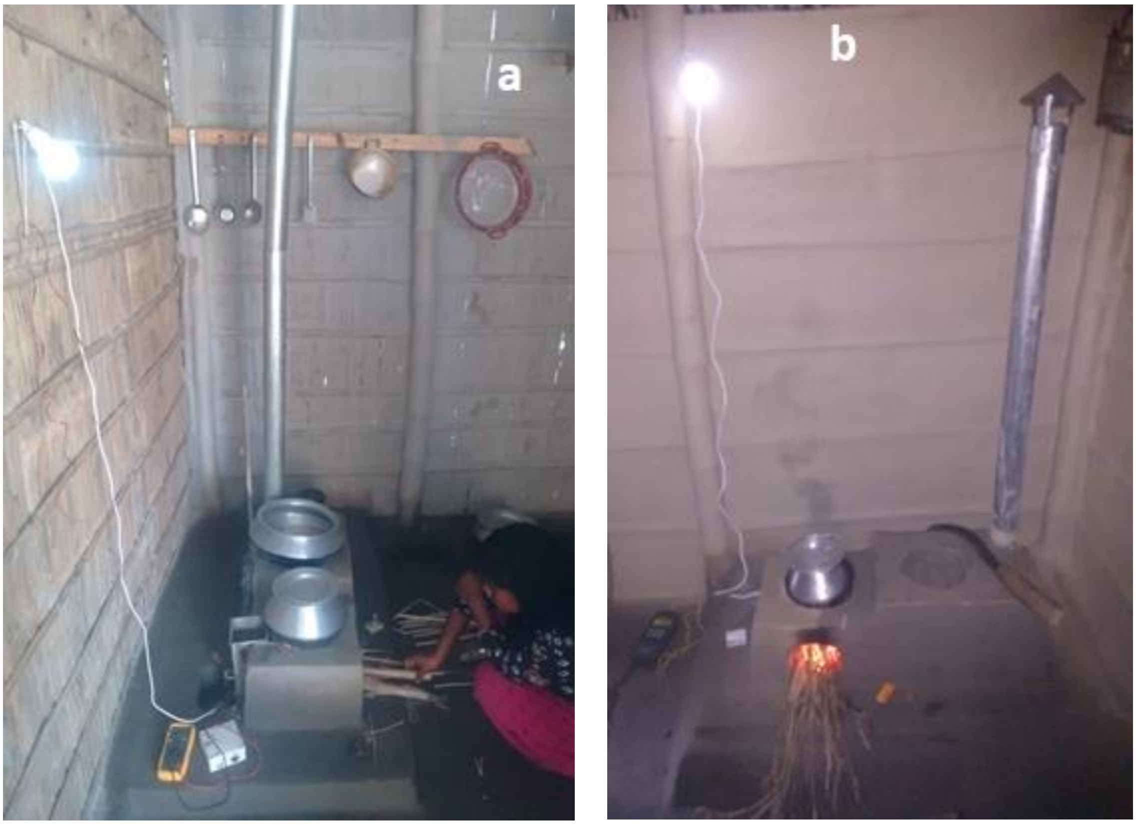


Fig. 4.17 Photographs of light illumination at households, (a) H2 utilizing illumination in cooking work space from TIFICS, (b) Illumination from TIFICS at H4

4.10. Issues faced during field testing

Several issues were observed during TIFICS deployment which caused interruption and hampered the performance of TIFICS operation. These issues were investigated and highlighted in the Table 4.8.

One of the issues faced during field testing was the users' interest and cooking custom. We have mentioned earlier that field testing at H5 could take place only for a period of two days. Awareness appears to be the prime reason for the lack of interest in using TIFICS. The household was habituated in using traditional cook stove and had an affinity towards it. This experience is useful for planning adequate awareness while attempting to deploy TIFICS in deprived regions. As a result, limited information of power production at H5 could be generated.

The controlled test conditions which was generally followed in laboratory tests was absent during field test. During laboratory tests, charcoal and ash built up within the combustion chamber was prevented in order to maintain a sufficient temperature for power production. During TIFICS deployment, there were instances where charcoal and ash have built up on the heat collector plate (Fig 4.9), particularly at H4, which prevented TEG to achieve sufficient hot side temperature to produce power.

TIFICS at H1 could not withstand the force exerted during fuel feeding and in the process the TEG assembly was disintegrated from the stove. Although, no such instance was encountered at other households, the incident at H1 have highlighted the need of a more reliable and robust structure.

Table 4.8 Issues faced during TIFICS operation

Household	Number of days of uninterrupted operation	Issues	Summary
H1	12	Mechanical failure	Users faced mechanical failure of TEG assembly while operating TIFICS
H2	54	Electrical failure	Thermal stress owing to high temperature gradient across the TEG module
H3	90	No issues	-
H4	90	No issues	-
H5	2	Mechanical failure	Lack of awareness

The TEG module at H2 showed disconnection of p-n couples from the solder attached on the substrate, formation of cracks on the ceramic substrate, disconnected output terminals from p-n couples, and ultimately causing the device to fail as shown in Fig 4.18. It was observed during field testing that the hot side temperature from 47th day to 54th day of TIFICS operation at H2 exceeded the safe limit of TEG hot side temperature of 330ºC which is shown in Fig. 4.14. Large temperature gradient for significant power production and thermal cycling can lead to thermal stress on TEG module [39-41]. Thermal stress owing to mismatch of coefficient of thermal expansion (CTE) values between ceramic substrate surface (8.1×10-6 K^{-1}), Bi_2Te_3 (16×10-6 K^{-1}) p-n couples and aluminium plates (24×10-6 K^{-1}) was most likely to have induced compressive stress on p-n couples which have led to internal crack during operation. Several researchers have also reported the effect of thermal cycling causing thermal stress. Degradation in power output and failure within 400 cycles was observed in a commercialized TEG module when the hot side temperature was kept at 180ºC and cold side temperature was maintained at 30ºC. The research group concluded that thermal stress arose due to mismatch of CTE between TE elements and metal contacts [42]. Another study showed 14% decrease in output power after 6000 cycles when operated at 200ºC [43]. In our field tests, prior to failure, the TEG module at H2 operated for 162 cycles and at temperature beyond the permissible limit of TEG.

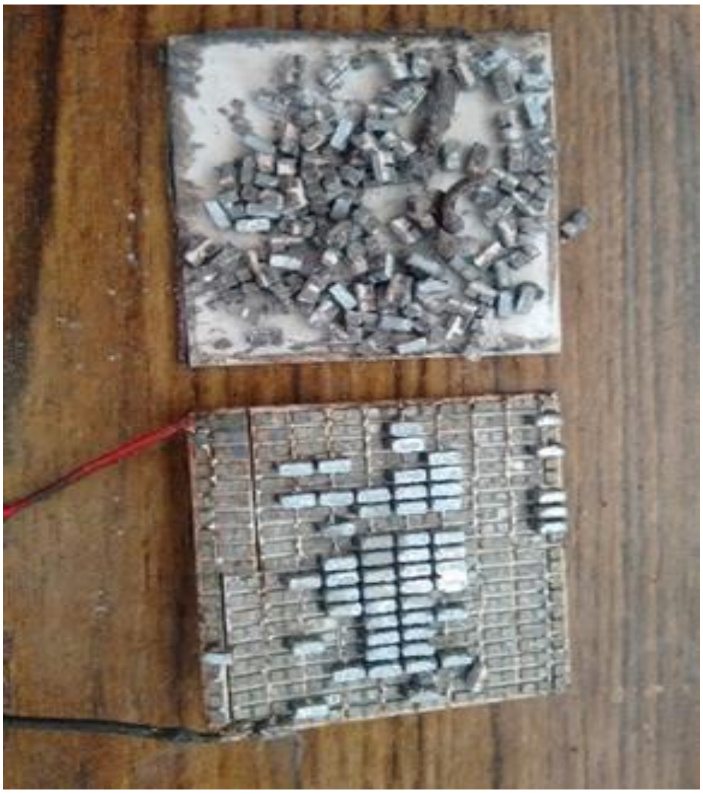


Fig. 4.18. TEG module with thermal stress at H2

Considering the issue of thermal stress, an extensive study is required to understand the TEG module under thermal stress induced due to mismatch in CTE and thermal cycling. The performance of TEG module and long term stability should be studied under different temperature gradients for 1000 cycles. Moreover, the study of thermo-physical as well as elastic properties of the modules is required as it determines the device's strength. The investigation of stress test of TEG to investigate electrical and mechanical failure for long term application was emphasized in an earlier research [9].

Further, during the TIFICS deployment phase, it was observed at all the households that LED was illuminated when TIFICS was in operation. The battery was charging and discharging at the same time and at wide rates. Such practice is significant in reducing life span of the battery. Also, on certain occasion, it was observed that users left the battery in a discharged state failing to turn off the USB switch while using it to charge their mobile phone. Hence, improvements in battery charging and discharge protection should be looked at to enhance efficient battery charging for longer life cycle.

4.11. Impact of TIFICS on users

The perception of users is an important aspect for any technology for its acceptability and adoption. Several features of TIFICS were valued by users and are presented in Table 4.9 in addition to certain difficulties during the deployment phase. These information were collected during a survey post TIFICS usage (Appendix D).

During the TIFICS deployment phase, users expressed their experience of using TIFICS and the changes they faced in their daily activities. Prior to TIFICS field tests, users used to cook in their traditional biomass fixed clay cook stoves (TBCS) and reported the issue of smoke build up in the cooking area. As a result, frequent visits to nearby health centre by women (the cook) suffering from chronic cough, added a burden of expenses on health check-up. Further absence of proper lighting in the cooking area as well as for children during study hours was another issue faced by the users during pre-deployment phase. Women and children have reported itching of eyes from the exposure of kerosene fumes from hurricane wick lamps and exposed wick lamps.

The addition of a chimney to take the flue gas out of the cooking area through natural draft prevented smoke build up which users have reported as a comfort inside the cooking area. Night time illumination from LED in TIFICS helped users’ reduction to exposure to kerosene fumes during cooking. School going children stated the importance of LED bulb illumination and prioritized TIFICS over their existing kerosene lamps.

TIFICS was observed to impact on health of users during deployment by reducing exposure to indoor air pollution and hazardous kerosene lighting thus assisting UN’s SDG3 i.e. promotion of good health and wellbeing.

Potential savings of conventional energy resources was observed and illustrated in Fig. 4.19 and Fig. 4.20. Changes in kerosene consumption was observed among four households with H4 saving the most. Three out of four household consumed 5L/month of kerosene on average whereas H2 consumed 3.5L/month during the pre-deployment phase. Two types of kerosene lighting options i.e. hurricane wick lamp (HWL) of 350ml capacity and exposed kerosene wick lamp (EWL) of 50ml capacity are used by each households.

There is a variation in kerosene savings among the households. During field testing, the average kerosene savings of H4 was observed to be the most (3.35L/month) among four households. H4 owns a single HWL and two EWL and during TIFICS operation, the hurricane wick lamp was not used thus saving majority of kerosene. Whereas, H1 owns two HWL and one EWL and during TIFICS operation one of the HWL was not used. H2 was the least consumer of kerosene during TIFICS operation. It is also important to mention that the demand of kerosene in H2 was also less (3.5L/month) compared to other households. Daily savings of about 50ml was observed from H2.

Overall, one lighting option i.e. HWL was not operated during TIFICS operation thus resulting in maximum savings. Annual savings in the range of 24-40L of kerosene can be expected among all the households through TIFICS usage.

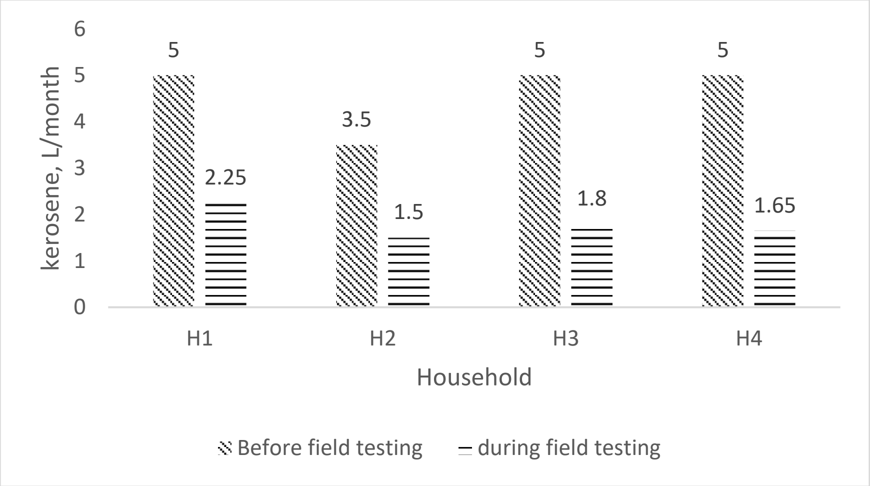


Fig. 4.19 Kerosene savings among households

Changes in firewood consumption was also observed during TIFICS operation and illustrated in Fig. 4.20. Sufficient amount of firewood use was observed to be reduced during field testing. An average reduction in the range of 4-5.5kg/day was recorded with H2 saving the most (5.5kg/day). The savings also attributed to time and monetary savings in firewood collection which is discussed in Chapter 5.

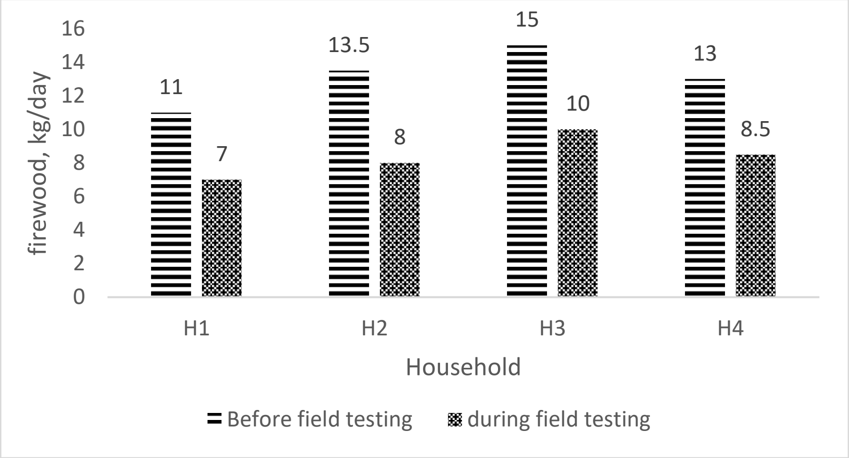


Fig. 4.20 Changes in firewood consumption

Table 4.9 Features valued by user

SN	Parameter	H1	H2	H3	H4
1	LED illumination	√	√	√	√
2	Phone charging	√	√	√	×
3	clean cooking	√	√	√	√
4	hot water	√	√	×	×
5	firewood savings	√	√	√	√
6	kerosene savings	√	√	√	√
7	Time saving	√	√	√	√
8	Fuel type and preparation	√	√	√	√

The provision of thermal energy output through hot water for drinking and cooking purpose was highly valued by users. Hot water obtained during simultaneous cooking operation and electricity production saved added firewood use.

The provision of cooking in two pots in TIFICS simultaneously was reported to save fuel and time in cooking which was valued by users. The three fold output (clean cooking, electricity production and hot water) from TIFICS was highly appreciated by users and users preferred TIFICS over TBCS.

The changes in energy sources (firewood and kerosene) also attributed to cost saving in addition to as well as income generation opportunity from time saved in cooking which could be utilized in purchasing food and basic essentials thus assisting SDG1 and SDG2 which states eradication of poverty and hunger. Savings in firewood consumption also reduced the time of firewood collection. Time saved by children which was earlier utilized in firewood collection can be devoted in quality education which assists SDG4. During pre-deployment phase, it is observed that women spend most of their time in the kitchen which makes women more prone to inhaling particulate matters. Using TIFICS, time is saved in cooking as well as firewood collection which prevents the inhalation of particulate matters primarily for women thus promoting gender equality i.e. SDG5. TIFICS provide clean cooking and electricity generation with benefits from firewood and kerosene savings as well as income generation from time saving which assists SDG7 i.e. clean and affordable energy.

Firewood savings attributed from TIFICS usage have an impact on the forest ecosystem. Quantity of firewood saved during TIFICS deployment reduced deforestation and emissions associated with climate change. The savings in firewood is believed to save forests from deforestation and maintain equilibrium in terrestrial life which in turn promotes UN SDG13 and SDG15.

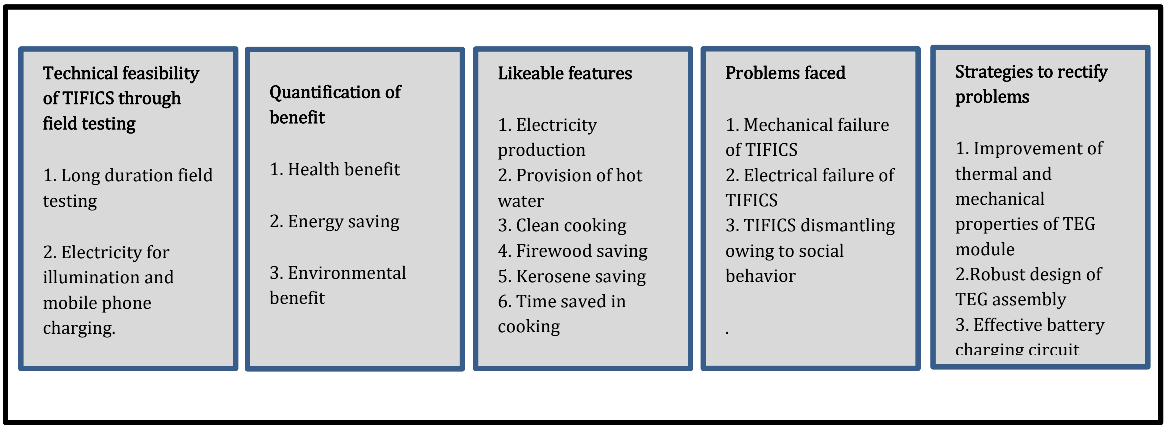
During pre-deployment phase, users used to fabricate TBCS on the basis of their needs of fuel size, type and feeding rate. The transition from existing cooking practice to an improved cook stove requires change in cooking habit viz., maintaining moisture content of fuel characteristics, cutting fuel in specific size and maintaining uniform feeding rate. Extra penalty or burden using TIFICS in terms of cooking with different vessels, and sizes of firewood was observed to be negligible. Users found TIFICS suitable in terms of fuel flexibility (firewood to agro residues), fuel size and feed rate which didn’t deviate from their cooking practice maintained in TBCS. During one instance, a household dismantled the TEG assembly from the cook stove which is caused due to fuel feeding behaviour. The issue was rectified by replacing the TIFICS with a new one.

Further, users have suggested their inputs in improving the design of fuel feed opening based on their usage. The thermal output in the form of hot water from the heat sink was highly valued since it used no extra firewood. No deviation in taste of food is reported using TIFICS.

4.12. Summary

A brief graphical summary is presented in Fig. 4.21. In this Chapter, TIFICS was identified to be technically feasible in rural area with lack of access of clean cooking device and lack of reliable access to electricity. TIFICS was capable of generating sufficient electricity to provide basic electrical needs of illumination and mobile phone charging. Users' response has been captured with quantification of electricity consumption and changes in energy sources consumption particularly kerosene. Negligible burden in terms of TIFICS usage was observed. New information to field deployment in terms of quantification of benefit, likeable features, and problems faced and strategies to rectify the problems are generated which was not available earlier.

In the next chapter, we have investigated the economic benefits of TIFICS on the basis of experiences gathered from field testing in addition to policy drivers for TIFICS promotion.



Technical feasibility of TIFICS through field testing

1. Long duration field testing
2. Electricity for illumination and mobile phone charging.

Quantification of benefit

1. Health benefit
2. Energy saving
3. Environmental benefit

Likeable features

1. Electricity production
2. Provision of hot water
3. Clean cooking
4. Firewood saving
5. Kerosene saving
6. Time saved in cooking

Problems faced

1. Mechanical failure of TIFICS
2. Electrical failure of TIFICS
3. TIFICS dismantling owing to social behavior

.

Strategies to rectify problems

1. Improvement of thermal and mechanical properties of TEG module
2. Robust design of TEG assembly
3. Effective battery charging circuit

Fig. 4.21 Graphical summary of the Chapter 4

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