CHAPTER 6

Summary and Conclusions

The lower electricity access leads to many difficulties for the people living in rural areas and therefore, has been a focus of this study. Dominancy of firewood consumption using traditional fixed clay made cook stove associated with loss of excessive heat has also been found as common feature in rural areas. Arrangement of nominal electricity for night time illumination and mobile battery charging, through recovery and conversion of waste heat from cooking stove, is expected to reduce the level of difficulties in typical rural areas till regular and reliable supply of electricity is ensured.

The present work aimed to develop a TEG integrated fixed clay cook stove (TIFICS) which collect, convert and deliver waste heat as electricity using the principle of thermoelectric effect. An improved fixed clay biomass cook stove was selected considering the dominancy of fixed clay stove users in the selected rural area. A systematic study to estimate thermo-physical properties of stove material, heat received and dissipated in the stove body was made. A TEG assembly comprised of heat collector, TEG module and heat sink was developed, mounted and integrated with the fixed clay cook stove to assess its technical feasibility. The working of TEG integrated fixed clay stove (TIFICS) under field condition with users' participation was investigated for a period of 90 days. Economic analysis of TIFICS and the policies for promotion of TIFICS in regions with lack of access to clean cooking and reliable electricity was discussed.

The major findings of the investigations are summarized below.

6.1. TEG integrated fixed clay stove

The first objective of the present work was to develop a thermoelectric generator (TEG) system for recovery of waste heat as electricity from fixed clay stove. The objective was fulfilled and new technical know-how was generated to develop a TEG assembly for a fixed clay stove. Laboratory results were adequate to prove the technical feasibility of generation of electricity for illumination and battery charging. The highlights of the results are briefly mentioned below.

- Estimation of thermo-physical property of the stove material indicated that it has lower thermal conductivity, lower thermal diffusivity and high specific heat compared to most common improved cook stove materials. The high density observed was responsible for high thermal mass for heat transfer. Thermo-physical properties correlated with the slow heat transfer rate from the combustion chamber inner wall to the outer wall thus storing part of the thermal energy during stove operation.
- The critical task in developing and integrating TEG assembly with fixed clay stove was experienced considering the vastness of options of heat collator material, TEG module, and cooling mechanism for heat sink. Aluminium was identified to be best material over copper and stainless steel for the heat collector plate in terms of strength to weight ratio and economics of material.
- Out of fifteen TEG modules, an appropriate TEG module was selected capable of operating at high temperature up to 400ºC and produce power (~8W) to operate basic electrical appliances for illumination and charge battery powered devices.
- Natural convection cooling with water as cooling fluid was identified to be the suitable cooling mechanism for heat sink for the present study with added benefit of no auxiliary power consumption to initiate cooling process.
- The components (heat collector, TEG module and heat sink) were assembled and integrated with the improved fixed clay stove to obtain TEG integrated fixed clay stove (TIFICS). Series of experiments were performed for a typical cooking cycle (1h) at different mode of operations (i.e. matched load, illumination and battery charging) to investigate the performance of TIFICS. At matched load condition, a peak electrical power output of 2.7W at a temperature difference of 231ºC was estimated. A linear relationship of output power with respect to temperature difference was observed following the laws of thermoelectricity.
- The prospect of illuminating a 3W LED bulb using direct electricity from TIFICS was investigated. Illumination for 65 min in a single cooking cycle was observed which shows the potential of TIFICS to provide illumination during power outage in rural area.

- A 3.2V 2.0Ah battery was fully charged from the TIFICS in 3.7h of operation. Owing to transient power production during the initial starting period of TIFICS, around 50 min of stove operation was required to attain a temperature difference of greater than 180ºC and reach the charging voltage (3.2V) of battery.
- A multi utility option was observed in TIFICS as along with electricity, thermal energy in the form of hot water from the heat rejected by TEG cold side to the heat sink was available. Water in the heat sink heats up to 73ºC from ambient (28-29ºC) during typical cooking cycle of TIFICS. Around 1kW of thermal energy as hot water was available from 10h of TIFICS usage.

6.2. Field Testing of TIFICS

Laboratory tests were adequate to prove the technical feasibility of TIFICS for electricity generation utilising waste heat from the stove. However, the performance of TIFICS in a rural area and user perception and response of it was required. As a result, the second objective of the present work i.e. to investigate the technical feasibility of TEG integrated fixed clay cook stove (TIFICS) in a typical rural area through field testing was set. Earlier, limited researches were available concerning the field testing vis-à-vis user perception of TEG integrated cook stove. In the present work, new information were available on performance of TIFICS under varying user cooking customs in addition to impact of TIFICS on user.

The deployment of TIFICS at five households in a typical rural area of Assam, India, was attempted and performance testing was carried out during a 90 day field testing. Information were collected during pre-deployment phase and during deployment of TIFICS to understand change in energy resource consumption and impact of TIFICS on users in terms of health and energy saving.

The findings of the field tests are highlighted below.

- A systematic survey was conducted during the pre-deployment phase and domestic energy use pattern in cooking and lighting was estimated in a rural village, Dikarijan lacking access to clean cooking and reliable electricity. The end use energy consumption in cooking through firewood was estimated to be higher compared to other modes of cooking. An estimated 30% of traditional fixed clay cook stove users did not have grid electricity access and thus depended on kerosene for lighting. Even with grid electricity users, kerosene lighting was most common during times of power outage which was observed to be around 3-4h during peak demand hours. The potential of TIFICS testing was recognized and five household (H1, H2, H3, H4 and H5) without clean cooking and electricity access were selected for 90 days of field testing.

- A positive response in terms of TIFICS usage as over 200 times of meal preparation was recorded with up to 449h of stove operation at four (H1, H2, H3 and H4) out of five selected households.
- The maximum achievable temperature difference obtained at H2 (255ºC) was higher compared to laboratory tests (231ºC), H1 (221.8ºC), H3 (216ºC) and H4 (209ºC) which also affected on the performance of TIFICS. Maximum temperature difference was influenced by higher TEG hot side temperature and lower TEG cold side temperature. The average hot side temperature was higher (320ºC) and cold side temperature was lower (69ºC) at H2 compared to laboratory and the selected households. Majority of tests conducted at H2 was during winter where the ambient temperature varied between 19-22ºC which also have impacted on the performance of H2.
- Firewood type plays an important role on TIFICS performance. Firewood at H2 was of high calorific value (18.28 MJ/kg) and hence higher power production can be correlated with it. At H4, a high moisture content (28%) along with higher ash content (11%) and lower calorific value (14.64 MJ/kg) have resulted in lower power output. During the final days of field tests, the hot side temperature at H4 was identified to be lesser compared to the initial days of test. The amount of ash layers deposited on the surface of heat collector plate was the evidence for the lower hot side temperature.
- Maximum power production was possible at H2 (3.2W) compared to H1 (2.6W), H3 (2.4W) and H4 (2.3W). The maximum power generation was attributed to higher achievable temperature difference at H2. TEG voltages at all the households during TIFICS operation were sufficient to charge the rechargeable battery. During

deployment phase, about 160ºC of temperature difference was required for the TEGs to obtain 3.2V which was the threshold charging voltage of the battery.

- Higher power output have resulted in overall higher electrical energy generation at H2 which is 476Wh. H5 generated the least electrical energy of 10Wh. Due to ash deposition on the heat collector plate, lower power generation during the final days have resulted in overall generation of 317Wh at H4..
- Majority of electricity consumption in the form of night time illumination was observed among all the households. Probably the importance of illumination was beyond any device charging and also the benefits it brought in kerosene saving. H2 consumed around 285Wh of electricity through lighting (227Wh) and phone charging (58.5Wh). Overall more than 150Wh of electricity consumption was observed among all four households during 90 days of field tests.
- Several issues were identified during TIFICS deployment phase which caused interruption in field testing. TIFICS at H2 attained electrical failure owing to thermal stress on TEG module. The TEG assembly of TIFICS at H1 was dislocated owing to users' cooking customs. Field testing of TIFICS at H5 could not be continued beyond 2 days owing to lack of awareness of the prospect of the technology. TIFICS at H1 and H2 were reinstalled and operation was continued.
- Users of TIFICS reported the comfort level of cooking in terms of reduction of kerosene exposure and reduced smoke inside cooking space, firewood and kerosene savings and better illumination level. Moreover, transitioning from age old cooking practice was not deviated while using TIFICS.
- The experience of users of TIFICS indicated that the technology (TIFICS) was able to support eight of the 17 Sustainable Development Goals through reduction of poverty, hunger, gender equality, promote education, improve health, ensuring clean and affordable energy access, protect climate and protect life on land. TIFICS is also able the support the present national (Indian) mandate through providing electricity and clean cooking at households.

6.3. Economic benefits and TIFICS promotion policy

There are several commercialized TEG integrated biomass cook stoves with variation in features. However, these cook stoves do not meet the existing cooking customs and even do not target the economically challenged sections and energy deprived regions of the world.

In the present study, a technology based on utilizing waste heat and its conversion into electricity with an aim to prevent issues of inefficient cooking and inadequate access to electricity was developed. The third objective i.e. to analyse economic benefits and policy for TIFICS promotion attempted to fulfil the potential of TIFICS as a marketable commodity and to identify policy drivers to promote the technology. The highlight of the findings are

- Economic merit of TIFICS was compared with prevailing cooking technologies viz. traditional biomass fixed clay stove and LPG cook stove using a parameter called levelized cost of cooking a meal (LCCM). LCCM of TIFICS was estimated to be 0.23US$ which is 53% lower than traditional biomass cook stoves (0.49US$) and 30% higher compared to LPG cook stove (0.16US$).
- Sensitivity analysis on increasing fuel prices indicated LCCM of TIFICS comparable with LPG. Although LCCM favours LPG in the present situation, TIFICS with its features of electricity generation, clean cooking, and thermal energy output makes it a prospective solution for dissemination in the rural area.
- TIFICS was associated with considerable firewood savings and kerosene savings which saved sufficient expenditures on field testing participating households.
- Several policy support for promotion of TIFICS as a rural technology were identified. Government can implement policies or add new policy in existing schemes to promote TIFICS with features of converting waste heat into electricity.
- A proper business plan was identified to be required for TIFICS promotion under many entrepreneurial drivers such as Start-up India and Make in India.
- TIFICS was identified to fulfil partially and fully the objectives of several national schemes in India relating to rural electrification, clean cooking and clean and efficient lighting.

6.4. Conclusions

Specific conclusions from the present research works are:

- New information related to assessment of waste heat and integration of TEG with a fixed clay cook stove was generated. It was technically feasible to utilize the waste heat from the fixed clay stove and convert it into electricity for illumination and charging battery, both of which are considered essential for population with lack of electricity access or unreliable electricity access.
- TIFICS was tested in a rural area and was valued by users due to its inherent advantageous features including (i) custom friendly design, (iii) clean illuminated environment at cooking space and (iv) additional benefits of battery charging and hot water, and (iv) firewood and kerosene savings.
- The benefits of TIFICS in terms of cost of cooking, firewood savings and kerosene savings make it a favourable technology over existing cooking devices.
- TIFICS is a useful technology to meet the electrical needs in cooking and study during critical period of load shedding. Thus, the adverse impacts of kerosene in such transition period is avoided. The requirement of electricity during such period was highly required which is attempted to be provided by TIFICS.

6.5. Practical usefulness of TIFICS

Usually, kerosene is used as an alternative fuel during load shedding hours. Usage of kerosene have many adverse impacts, particularly, among women and children. Provision of adequate illumination for cooking as well as for study through TIFICS is expected to reduce the dependency of kerosene.

Another common issue of rural area is the difficulty to charge mobile phone due to uncertain supply of grid electricity. The provision of electricity for mobile phone charging through TIFICS is expected to reduce the drudgery.

6.6.Suggestions for future work

The investigation of the present research was aimed for a typical rural section of the society deprived of quality energy access. TIFICS was developed and tested at laboratory and field following standard procedures. Additionally, sufficient effort and investigation might be required with minor refinement to address the issues of further dissemination and adoption. These are.

- The cold side temperature attained at the end of each field experiments is close to 73ºC. The design of the heat sink could be improved so that cold side temperature do not exceed to at least 10ºC of the ambient temperature.
- Improvements in battery charging and discharge protection should be looked at to enhance efficient battery charging for longer life cycle.
- TEG module during field tests exhibited electrical and mechanical failure owing to thermal stress. The performance of TEG module and long term stability should be studied under different temperature gradients for 1000 cycles.