MECS-TRIID Final Project Report

A solar PV based low cost inverterless grid integrated cooking solution

Date: January 29, 2020

Produced by: M. Rezwan Khan

For: DFID and Loughborough University

Contact Details:

Prof. M. Rezwan Khan

United International University

United City, Badda, Satarkul,

Dhaka Cell phone: +8801716 048

946 URL: www.uiu.ac.bd

Document Control

Issue Status	Author(s)	Reviewed By	Loughborough University Approved By	Issue Date
Draft version	M. Rezwan Khan & Intekhab Alam	Simon Batchelor		23/03/2020
Final version	M. Rezwan	Simon Batchelor	Jane Spencer	7/05/2020

Executive Summary

The recent trend in the falling price of the solar PV has made solar PV based electricity less expensive than the grid in many of the developing countries. In this project, we proposed to develop a grid integrated solar PV based cooking system which will be low cost and environment friendly solution requiring minimum possible change in habit for the users. We thought of an inverter-less system to get rid of the inverter, one of the costly components, to keep the energy cost low. The cooking system was designed to work with DC voltage and solar PV is integrated to grid in such a way that it operates close to the maximum power point. The electronics is designed to give priority to the PV power while cooking and any short fall in power is compensated by the grid. Although, we used DC voltage as the input to the appliances connected to our cooking system, we ensured that our system is compatible with the appliances readily available in the market and no modification is required while using them. So, we tested hotplates, induction cookers and Electric Pressure Cookers with our system and found that all of them worked well under DC voltage environment without the necessity for any modification. The final version of the control circuit is developed to produce variable DC voltage at the output so that the power delivery to the cooking appliance can be varied as per requirement.

Although, most of the cooking appliances have their power rating varying from 900-2000W, it has already been demonstrated that it is possible to cook with less than 500W [Batchelor et.al., Energies, 11(11), page 2933, 2018] of power if heat loss from the cooking system can be minimized. The hotplates are usually made from metal structures and can have significant heat loss from its surfaces. So, we insulated the hotplate by putting insulating wools in the empty space inside the hotplate and put an insulating sheet (glass fibre) to reduce heat loss from the bottom, side walls and the top surface of the metal structure respectively. No additional insulation was tried for the induction cooker or the electric pressure cooker as they seem to have reasonable insulation in them. We also designed an insulating cover for the cooking pan, which is easy to use, very low cost and does not require any major change in habit. There are cooking pans and pots available in the market where the side walls and the lid have insulating layer so that heat loss is significantly reduced. However, they are quite heavy, not too easy to handle while washing and cleaning and above all quite expensive for the poorer section of people in the developing world. The insulated pan cover we developed is light weight, very simple in design and is quite easy to handle. Results show significant improvement in heat retention performance when insulated cover is used with conventional pots and pans. Considering energy saving in cooking with pressure cookers, modern day cooking is gradually moving towards pressure cooker based cooking, wherever appropriate. An electric pressure cooker is quite well insulated and is energy efficient. On the other hand, the conventional pressure cookers have no extra insulation and heat loss from the cooker walls and lid surface is higher when compared to that of electric pressure cookers. But if we consider the cost, an electric pressure cooker is 3 to 5 times more expensive than a conventional pressure cooker of similar cooking capacity. So, we feel that there will be significant number of users in foreseeable future who will be using electricity for their cooking but may be interested to use conventional pressure cookers due to their lower cost. So, in our experiment we compared the cooking energy efficiency of an Electric Pressure Cooker (EPC) to a conventional pressure cooker with insulating cover. Our results show that conventional pressure cookers could be a formidable competitor to the EPCs. It is important to mention that we could not use induction cookers while using conventional pressure cookers as they are made from aluminium and is not recommended for the induction cookers. So, all the experiments with the conventional pressure cookers were done using hotplate. In our experiment, when chickpeas were cooked, the conventional cooking

consumed 1.03 kWh, conventional pressure cooker consumed 0.25 units and EPC consumed 0.21 units of electricity.

We used two sets of solar PV array for two different circuit arrangements, one at 162V DC and the other at 310V DC. The 162V system was first designed to use the cooking appliances at a lower voltage so that the power consumption are lower than rated. We tried cooking appliances having the following ratings – hotplate 1200W, induction cooker 1800W and EPC 900W. When used with our 162V system, the actual power consumption for the hotplate and the induction cooker was 610W, 625W respectively. We changed the operating voltage to 145V by changing the voltage tapping point of the transformer. After choosing the new tapping, the power consumption of the hotplate, induction cooker and the EPC was 480W, 510W and 390W respectively. The lower consumption of power was due to the lower DC voltage that we chose. Reducing the appliance power was important to enhance the power share from the PV. If the power consumed by the appliance is maintained less than 500W, the power sharing of the PV and the grid under different sunshine conditions can easily be maintained close to 75% on a clear sunny day if cooking is done between 10am and 2pm, the usual cooking hours in Bangladesh. The percentage can be lower if there is cloud and fog. Considering the available average sunshine in Bangladesh (4.5kWh/sq.m), a 500W cooking system on an average is expected to draw close to 65% of its energy from the PV. The size and weight of the transformer used to step down the grid voltage to the compatible DC voltage of 145V was high and we decided to go for a second design where no transformer is needed.

To utilize the solar PV energy that is generated during the non-cooking hours a water heater was connected to the PV system and was switched ON whenever there is surplus energy in the PV. The surplus was sensed by monitoring the PV voltage and whenever the PV voltage exceeded 165V the water heater was switched on. We used a hot water dispenser having a water storage capacity of 6 litre and on most of the sunny days the temperature of the water dispenser reached more than 80°C by 10am when we started our cooking experiment. It is proposed that hot water from the dispenser will be used when food for cooking is put on the cooking appliance. As the food is at the room temperature, adding water of 80°C to it will make the temperature of food and water combined close to 60°C. While cooking chickpeas, the EPC energy consumption was reduced 0.21 kWh to 0.16 kWh when hot water (temp. 95°C) was used. This corresponds to an energy saving of 25%.

In our proposed system, the cost of the solar PV system (500Wp) with control circuit is estimated to be GBP 285 including installation. The average cost of cooking energy is estimated to be GBP 3 to 4 per month for a family of 5 persons, depending on the choice of the appliances they make for their cooking. This is much lower than the cost for fire wood (GBP 5.0/month), gas cylinder (GBP 7.0/month) and conventional electric cooking (GBP 10.0/month). This cost includes the estimated energy cost supplied by the solar PV based on it's the system cost (GBP 285). So, the actual monthly bill to be paid for the grid energy will be less than 40% of the cost that we have mentioned here (assuming 60% energy comes from PV).

We applied for time extension to develop a new control circuit that would replace the transformer-based control circuit by power electronic circuits (the transformer being used to step down the grid AC voltage from 220V to 120V). Unfortunately, due to the outbreak of corona virus infection in China, we could not get the right electronic components in the market and we also failed to get them imported from Cine due to lockout. However, we got some AC-DC converters in the local market names as 'LED' drivers and used a combination of them to get the required voltage at the output. The final circuit that we used had an DC output voltage of 126V and accordingly, we reduced the PV output voltage by reducing the number of panels in series from 5 to 4 to operate close to the maximum power point voltage (the experimental setup and the results are presented in appendix C). This however reduced the output power of the array from 500Wp to 400Wp. Choosing an operating voltage of 126V DC reduced the power consumption of the cooking appliance less than 500W, which was our target right from the beginning. The voltage regulation of the AC-DC converter was very good and the voltage remained fixed at 126V when the power from the grid was varied. So, it seems that a AC-DC converter instead of a transformer can be an attractive solution if the AC-DC converter can be obtained at a cost less than GBP 30.

We also used a pyranometer to measure sunshine and correlate it with the PV power output. The results are presented in the Appendix C. The power extraction from the panel was close to 90% considering all the losses (losses in the power cables, losses inside the control circuit and the loss due to some deviation from the actual power point).

Table of Contents

1. Introduction

Despite the economic development of the less developed Asian and African countries over the last decade, more than half of the world population still uses biomass [1,2] and are subject to health hazard from the toxic fumes from the stoves [3]. Although the SDG7 sets the goal for affordable and clean energy, development of a low cost clean cooking technology is still a challenge. So, there is enough scope for research and innovation in this field. An adaptable low cost clean cooking technology has a number of impacts that can have global implications such as -

1. Reduction in GHG emission
2. Improvement in the quality of life at the bottom of the pyramid
3. Mitigation of gender discrimination as women are mostly affected by lack of kitchen hygiene
4. Contribute in poverty alleviation due to lower cooking cost and reduced health hazards

The main challenge for clean cooking in the developing countries is the cost of cooking. There may be limitations on the availability of certain cooking resources in particular geographical locations, but such unavailability of resources are ultimately reflected in the cost. Under privileged people in the developing countries predominantly tend to use charcoal or biomass due to their relative low cost. However, looking at the conventional biomass cooking, the stoves are inefficient and can cause health hazard. Gas cookers, although may not have the same high efficiency as an electric cooker, are more efficient compared to the conventional stoves and pose less health threats. A recent research [4] shows that using electricity with the adoption of appropriate loss reduction mechanisms, it is possible to cook using less than 500W and the cost of solar PV based cooking in an off-grid area, having battery backup, may be comparable to the usual charcoal based cooking.

In grid connected areas, electric cooking could be an attractive solution if the cooking efficiency and the cost of cooking could be reduced. One of the challenges that electric cooking faces is the relatively high energy requirement for cooking. If electric cooking in the households become popular, it may overload the existing power lines and the tariffs are usually set to discourage such higher electricity consumptions. Considering the falling price of solar PV, the cost of electricity at the panel end (excluding the cost of inverters, batteries etc.) is usually less than that of grid power.

If roof top PVs can be used via some innovative circuitry avoiding grid tied inverters and use grid as the backup instead of battery, it is possible to locally generate low cost electricity that can supplement grid electricity. This will reduce the overall electricity cost (eliminating inverter can reduce the PV electricity cost by around 30%) and at the same time reduce the chance of transmission lines being overloaded.

The issue of reliability of electricity supply due to grid failure or bad weather condition is important, but we assume that there will be alternative cooking facilities like biomass or gas based cookers in the households to address the electricity failure.

---

[1] US Environment Protection Agency. 2015. Availableonline:https://www.epa.gov/air-research/clean-cookstove-research.

[2] WHO. 2018. Available online: http://www.who.int/airpollution/household/en/ .

[3] Jetter,J.J.; Kariherb,P. Solid Fuel Household CookStoves: Characterization of Performance and Emissions. *Biomass Bioenergy* **2009**, *33*, 294–305.

[4] Batchelor et.al., Energies, 11(11), page 2933, 2018.

Aims of the project

The aim of the project is to develop a low cost grid integrated solar PV based clean cooking system where the users will also get the financial benefit of higher efficiency. At the same time, there will be significant penetration of green energy even in the grid connected areas, as expanding grid is becoming a threat to many of the renewable based power generation systems in the developing countries. With the successful implementation of the project, we expect the following outcomes

1. Low cost efficient cooking solutions that can be adopted by the poorer section of population
2. Significant percentage of green energy sharing along with the grid to reduce greenhouse gas emission
3. Zero emission cooking system reducing the health and fire hazard for the users
4. To reduce pressure on the grids when electric cooking becomes wide spread.

Objectives of the project

In this project, we identify the cost of clean energy and its accessories as the main hurdle towards adopting clean cooking technologies. With falling price of the solar PV, solar PV based cooking can be an attractive solution in the grid connected areas, where grid will be supplementing any shortfall in the solar PV power. In this project we propose a low cost grid connected solar PV based cooking solution with specific emphasis on the following aspects

1. Designing a low cost system
2. Enhancing cooking efficiency to reduce energy consumption
3. Inverterless integration of Solar PV with the grid for lower cost and increased efficiency
4. Storing of surplus energy from the solar PV in the form of water heating, the hot water to be used for cooking
5. Independently run by solar PV even when the grid power fails (a grid tied inverter cannot deliver power when grid fails)

While implementing the above mentioned features, care is taken to introduce minimum ‘change in habit’ so the users do not find it difficult to adopt in different cultural or geographical locations.

2. Methodology

We took an experimental approach for the project and our methodology had the following steps.

a) Identifying the possible sources of heat loss in cooking appliances and taking appropriate measures to minimize heat loss.

b) Ascertain that the appliances work under applied DC voltage without the necessity for any modification in them.

c) Design a solar PV array such that it can, on an average supply more than 60% of the cooking energy if the cooking power is less than 500W.

d) Design a control circuit that is inexpensive and can integrate solar PV with the grid using DC link such that power sharing between the solar PV and the grid is absolutely smooth. The control circuit diverted power to a water heater to store excess PV energy by heating the water.

e) After installation of solar PV array and fabrication of the control circuit, we tried cooking food in our systems to see how much power is needed for different food under different cooking appliances.

f) The experimental results are then analysed to determine the energy savings in different appliances for cooking the same types of foods.

g) Finally, a financial analysis is done to estimate the cost of the systems and cost of energy needed for cooking food in a family. A comparison is also made with the cost of cooking while using gas cylinders.

Outline of the concept

This project targets to maximize the use of solar PV, which has become quite inexpensive in the recent years and at the same time reduce the cooking energy drawn from the grid by enhanced efficiency and right choice of the cooking appliance. While using PV as an energy source, we face two major difficulties – first is the reliability of sunshine and second is the utilization of the PV energy when cooker is not in use. In grid connected areas, it is a common practice to connect the solar PV to the grid via grid tied inverter, so that the power at the electric cooker is ensured and excess power from the PV is delivered to the grid so long the grid power does not fail. It is expected that households will have alternative cooking arrangements like gas cylinder or biomass based cookers so that they can be used in case of emergency like when the grid fails. In case of small sized grid tied inverters less than 2kW, the cost of the inverters are high enough to increase the energy cost of a grid tied solar PV system higher than that of the grid power. So, in grid connected areas cooking with solar PV based electricity is not a popular solution. In this project t**he main innovation lies in the design of the control circuit that will eliminate the use of an inverter and use grid as an energy backup to supplement the short fall of power from the PV due to variable weather conditions. In case of surplus PV power the control circuit will deliver excess PV power to a highly insulated water heater.** The water heater will store the energy in the form of heat so that the hot water can be used for cooking. As usual cooking (other than frying) does not require the temperature to go above 100C, using hot water for cooking will significantly reduce the cooking time and energy requirements. The control circuit converts the grid AC supply to DC and will be connected to the DC output of the solar PV (which is to be designed to produce a DC voltage close to the grid voltage). Both the electric cooker and the water heater will be operating with DC voltage and no DC-AC conversion will be necessary. In the proposed design, number of solar panels will be connected in series such that they will operate close to the maximum power point voltage and the power sharing between the grid and the PV will have an efficiency (~98%) much higher than that of the usual small sized grid tied inverters (~90%). The block diagram of the proposed system is shown in Fig.1.

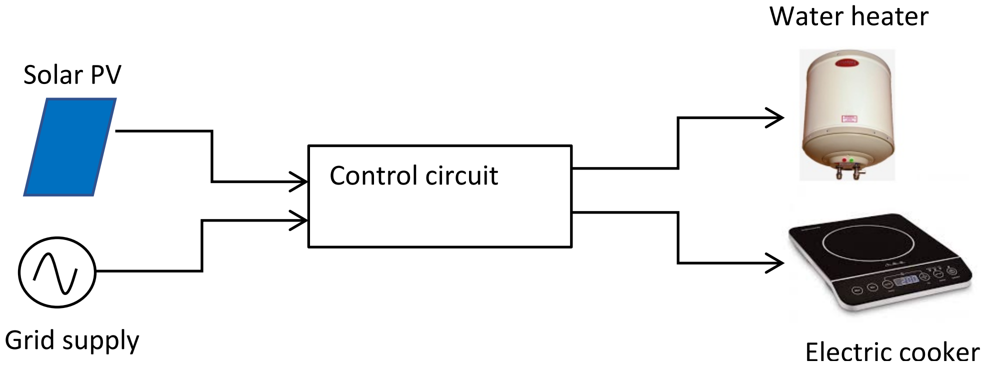


Fig.1. The block diagram for the proposed cooking system.

System description

The Solar PV panels: The solar PV panel will be using a number of panels in series such that the PV maximum power point voltage is close to the grid voltage. We plan to have a total PV panels of 500Wp. As we propose to insulate our cooking pans so that the heat loss is minimized and the actual power needed for cooking will be less than 500W.

The control circuit: The control circuit is basically an AC to DC converter that uses diodes. It rectifies the AC grid input to DC and is connected to the PV output on the DC side. The output voltage of the solar PV can vary significantly with the load, where as the grid voltage approximately remains fixed. So, the PV output voltage will adjust in such a way that the load power will mainly come from the solar PV, grid power only supplementing any short fall. If the cooker is off or put to very low power level, the PV voltage will tend to rise and a voltage sensitive chopper circuit will be activated to deliver excess power to the water heater. It is ensured in the design that no grid power will be used for water heating.

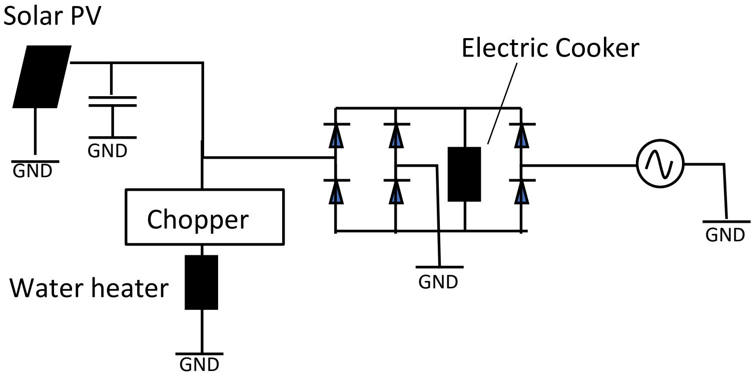


Fig.2. The internal arrangement of the control circuit.

The electric cooker: The electric cooker will be conventional hotplates or induction cookers. We will choose the cooker such that they adapt to the output DC voltage of the controller circuit. We only propose minor modification in the electrical design of the electric cookers, but we may enhance the insulation of the electric cookers to reduce heat loss.

The water heater: Water heaters usually use resistive heating elements and are insensitive to AC or DC supply. We propose to use the heaters available in the market without any electrical modification. Like the electric cookers, we propose to add extra insulation to reduce heat loss. A thermostat will be placed so that the water temperature does not exceed 80C. Uncontrolled water temperature may cause the water to boil and that will result in heat loss in the form of steam.

Besides the above mentioned components, we also plan to design flexible insulation jackets that can be strapped to the pans for reduced heat loss. After the water starts boiling, the pans will be taken off the cooker to an insulated resting place so that cooking process continues even after the pan is taken off the cooker. This will ensure significant energy saving using the principle of 'wonder bags'. The basic idea is depicted in Fig.3.

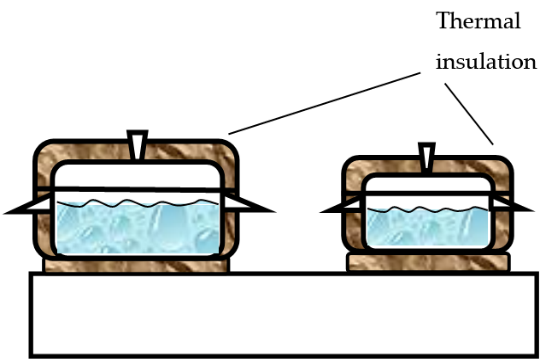


Fig.3. The schematic diagram of insulted resting place for the cooking pans

Another attractive feature of the proposed system is its independent mode of operation. In case of a grid tied inverter, the PV power will be wasted when the grid fails. In the proposed design, the cooking system can still work if there is enough sunshine.

For the sake of cost comparison of the proposed system with respect to the grid tied inverter based system, it is worth mentioning that the hardware cost including the water heater will be less than half the cost of the inverter based system.

Intellectual Property Rights

The intellectual property right will remain with the researchers, i.e., M. Rezwan Khan, Intekhab Alam and Arifur Rahman Talukder, if MECS does not have any additional terms and conditions.

Assumptions made

The assumptions made are

1. It is presumed that cooking is mainly done during the day time so that solar PV output is utilized in cooking. However, the system can work equally well at night as well but cannot utilize the solar energy effectively.
2. Project assumes that the technology will be adopted by the users based on their economic and hygienic considerations, no subsidy is considered in the cost analysis of the system.
3. The project will be effective in the geographical locations where the yearly availability of sunshine is high enough so that the cost of PV energy is less or comparable to the grid energy.
4. The insulating pan cover designed will not require significant change in habit.

3. Implementation

The work conducted

The project was a lab based one and we established our own setup for the project. It included procurement and preliminary testing of the cooking appliances, insulating the cookers where needed, designing and fabricating insulating pan cover, procuring the solar panel array and installing them etc. First set of experiment was water boiling test and then we cooked foods like rice, chickpeas etc. to see the energy consumption for different cooking appliances. We also collected the energy sharing data from the solar panel and the grid. Details are presented in the progress reports in Appendices 1,2 and 3.

In the context of Bangladesh, this project has a gender bias towards women, as the main beneficiary of the project is women involved in house hold cooking. We feel that gender equality is usually aimed to make sure that women are not left out and our project mainly concerns the benefit of women. This project will improve the kitchen hygiene for the working women themselves and their nursing children, resulting in less exhaustive work with reduced risk of fire or accidental hazards.

The project findings

Progress reports appended in appendices 1,2 and 3 provides the details of the project progression and the experimental results and analysis. The project findings can be summarized as follows

1. If heat losses in a cooking system can be reduced, it is possible to cook using less than 500W.
2. Using more efficient appliances like pressure cookers, it is possible to reduce the energy requirement by a factor more than 5 for foods, like chickpeas or beef, that require longer cooking time.
3. An inverterless integration of solar PV is low cost and quite effective in power sharing between the solar PV and the grid. In a country like Bangladesh more than 70% of the cooking energy can come from an PV array of 500Wp.
4. Instead of using a battery as an energy storage, water heater was used to store excess PV energy in the form of heat. Using hot water from the water heater could save around 25% of the cooking energy. Battery as a storage device is 5-6 times more expensive compared to the water heater.
5. Cost of PV and the control circuit including installation cost is approx. GBP 285. Cost of cooking energy is GBP 3-4 for a family of 5, where cost of fire wood is GBP 5, gas cylinder is GBP 7 and conventional electric cooking is GBP 10.

Limitations of the innovation/approach/design/system

Unlike the conventional grid tied systems where solar PV is connected to the grid via grid tied inverters, the proposed system cannot export energy to the grid in the form of feed in tariff or net metering.

Due low cooking power, Tthe solution is not equally attractive for cooking all types of foods particularly when cooking involves dip frying.

As the system was tested in the lab environment only, some of the limitations that we cannot predict at this point may arise once it is implemented/tested in the field.

4. Practical applications of the concept to the national cooking energy system (including costs)

National grid is expanding fast in Bangladesh and it is expected that more than 90% of the population will have access to grid electricity by 2021. There is also a comprehensive plan to generate 30,000 MW within next 5 years. It is envisioned that there will be significant surplus of electricity if the consumers are not made aware about the possible multifarious useful usage of electricity. The basic power need for the bottom and the upper bottom of the pyramid is based on light, cooling fan, TV, mobile changer and small sized refrigerator. Due to increasing efficiency of the electrical appliances, actual energy consumption for all these loads are not high and it is important to look for alternative use of electricity. Cooking by electricity can be a very good alternative as it is a primary need for each household. Govt. of Bangladesh is also considering to promote electricity based cooking as a component of its clean cooking policy and targets that 100% of the households should have clean cooking by the year 2030.

One adverse effect of grid expansion is its threat to the already established solar PV based systems. In all the stand alone off grid solar PV based energy generation system, battery is a major component for the reliable power supply and its adds more than 60% into the energy cost. Presently, cost of electricity in these isolated mini grids or solar homes systems are more than 3 times the cost of grid energy. So, as soon as he grid reaches an ungrided area, solar PV based systems are the first casualties. However, falling PV prices has made the PV electricity much cheaper than the grid electricity if innovative ways of using them can be devised. As our cooking system integrates solar PV to make the overall energy cost lower than the grid energy, such an idea can have an attractive application just based on the economic considerations. As per our initial estimate, the PV system with installation will cost GBP 285, cooking appliances will have an average cost of GBP 50. The expected energy cost for a family of 5 will vary from GBP 4-5 per month depending on the appliances they use, which is much lower than the average monthly energy cost of GBP 5.0 for cooking with fire wood, GBP of 7.0 with gas cylinder and GBP 10.0 with usual electrical appliances. At the same time, the system is expected to consume solar energy by more than 60%, which in turn will reduce GHG emission (assuming that the conventional grid power emits GHG) and improve carbon footprint of the country.

5. Next steps (e.g. beta or field testing and implementation; more development etc)

The energy requirement for the proposed cooking system is expected to be less than 30% of the energy required in the conventional electric cooking systems. Additionally, solar PV is integrated with the system that reduces the overall energy cost and boost green energy share at the national level. It is expected that the cooking system will consume more than 60% of its required energy from the solar PV and will not put any heavy pressure on the national grid if people switch over to the electric cooking system.

If we consider the components of the capital cost, they include the following components

Item	cost, GBP
Cost of solar PV (500Wp) with frame and connections	250
Cost of the hotplates	15
Cost of induction cookers	35
Cost of electric pressure cookers	100
Cost of the insulating materials for pan cover	1.25
Cost of insulating materials for Hotplate	7.5
Cost of the control circuit	35
The total cost for the energy system (excluding cookers or pans)	250+35=285

The total cost for the energy system (excluding, cookers or pans) - GBP 285

Cost comparison of cooking energy for a family of 5 members

Cooking with LPG – GBP 7/month

Cooking with biomass – GBP 5/month

Cooking with electricity (conventional) – GBP 10/month

Cooking energy cost* (using pan cover with hotplate or induction cooker) – GBP 4.0/month

Cooking cost with Electric pressure cooker (30% cooking done in EPC/ conventional pressure cooker**) – GBP 3.0/month

*The cost analysis presented above is based on energy consumption estimate of a household with 5 members. They are expected to consume approx. 95 kWh a month when conventional electric cooking is used. It will reduce to 32-45 kWh per per month with efficient cooking system as proposed here. In energy cost calculation, we considered the higher slab of tariff of GBP 0.085 per kWh. For lower tariff group the cost will be even lower.

**We found in our experiments that although there is more energy saving with EPCs when compared to conventional pressure cookers, the difference in energy cost will be marginal so we mention the same monthly cost for both the cases.

In the cost components given above, cost of the system, excluding cooking appliances or cooking pans, is GBP 285. It is important to understand that EPCs are not suitable for all types of cooking. The cost of a single EPC will be of the order of GBP 100, whereas the cost of a conventional pressure cooker is only GBP 15-20. So, the poorer households who want to switch to electric cooking will have the preference to go either for hotplate or induction cooker and maybe tempted to use the conventional pressure cookers as they can use other pots and pans in their cookers, which will not be the case with EPCs.

So, in estimating the cost of a follow up project we will assume an average cost where certain percentage of people will be likely to use EPCs and at the same time users will have the choice to buy hotplate or the induction cooker. We assume that (wild guess, as we do not have any study on this) 20% will opt for EPCs, 50% for hotplates and 50% for induction cooker. So, the expected average cost of the system will have the following breakdown of the costs.

PV with installation = GBP 285

20% of EPC = GBP 20
50% of hotplates =GBP 7.5
50% of induction cookers= GBP 17.5
Three units of insulated pan cover= GBP 3*1.5= GBP 4.5
So the average total cost of the package will be GBP 334.5.

Estimated cost for field implementation

If we want to field test the idea in 100 households, the estimated cost of the project will be

System cost = GBP 33,450

Cost of installing the systems = GBP 5,000

An implementing agency needs to be involved to install and monitor the systems and at the same time for data collection (for 6 months) and the estimated cost would be GBP = 35,000

So, we estimate that the total cost involvement for a project that implement electric cooking systems in 100 households will be GBP 73,450.

Dissemination Plan

The project was totally lab based and there is no field level implementation at this stage. However, we presented our research in some forums (including Sustainable and Renewable Energy Development Authority SREDA) and apparently people are taking interest. But we have not chalked out any specific plan for this as we have not received any commitment as such. SREDA has formulated a ‘Country Action Plan for Clean Cookstoves’ and is taking an initiative to implement clean cooking country wide by 2030. We are also considering to apply for MECS/UNICEF/SREDA funding for implementing the concept in the field.

So far the outcome of this project is concerned, we plan to publish a paper in a journal or a conference. We also plan to present our findings to policy makers and to local appropriate forums.

6. Conclusion

Clean cooking is an important issue considering the health hazard for more than 3bn people of the developing world and greenhouse gas emission from conventional cooking. It has been shown here that cooking, although considered as a high energy process, can be done using much less energy than usually anticipated by reducing the heat loss and can be a moderately low energy process. It is our observation that ‘temperature cooks not the heat’ and our experiments show that a rural family of 5 people can cook with only 45 units of electricity consumed over a month. Introduction of Electric Pressure Cookers (EPCs) is an additional positive element in efficient clean cooking. However, all types of food cannot be cooked in EPCs and it is more effective when long time boiling of foods, like beef, chickpeas or lentils, are concerned. In our experiments we found that many of the cooking processes can consume low energy if some additional control of the cookers are adopted. As for example, while cooking rice in hotplate or induction cooker using normal cooking pans, we switched the energy supply off once the water temperature just reached close to boiling. It was observed that the energy requirement was marginally higher when no insulating pan cover was used indicating that losses occurring from the cooking pan was not high till the water had boiled and energy was lost via the escaping water vapour. So, we feel that adopting a temperature control mechanism that will keep the water temperature close to 100°C but preventing the water from boiling can save heat loses.

In our project, we introduced a water heater that was storing surplus energy from the PV in the form of heat. Our experiments show that it is possible to save more than 25% of the cooking energy if hot water from the water heater is used while cooking.

We also tried a number of other household appliances/gadgets like light, TV, computer, mobile changing etc. with our system and found that they operate without any difficulty when connected to the DC line that is used for cooking. It opens up an opportunity to alternative use of the solar energy when cooking is not done.

7. Appendix

Appendix A: Progress Report 1

Summary: Considering the time frame (six months), it is a short time project and we need to develop the cooking solution within this time frame. Also, the developed design should be such that we should be able to replicate with minimum effort, if there is a decision (from the funders) to implement the system to study its field performance. So, we decided to choose components which are readily available in the market and needs minimum modifications while integrating to the cooking system. With this view in mind, we surveyed the market to see what components are available that can be used directly in our designed systems. As mentioned in the proposal, we are looking for low power cooking solution and need to select hotplates, induction cookers or water heaters having power rating less than 500W. It seemed to be the main challenge, as most of these components available in the local market have a power rating of 1000W or above. Although all the components that we get in the local market are designed for AC application, we need to test their suitability in DC, as we propose to use DC voltage in our cooking solution instead of AC. Performance of the cookers including hotplate and induction cooker has been tested and results are presented in the report.

As already mentioned that we will be designing cooking system that will consume less than 500W for cooking, it requires very good insulation for the cooker, the water heater and the cooking pans. However, the insulating system should not be such that it makes the cooking process very different for the conventional users requiring major ‘change in habit’. Design of the insulators and measured results are presented to show the reduction in the heat loss when insulation is used.

The control circuit for the solar panel has been designed and fabricated but is yet to be tested in the lab. We expect to get the test results by mid of November.
Detailed of our activities are given below.

1. Hotplate

As we surveyed the market, we found that there are hotplates of varied power rating ranging from 1000W to 2000W with a voltage rating of 220/230V AC. Almost them all of them have a heat control knob that can be used to reduce or increase the heating. On investigation we found that the heating control is implemented using thermostats and the position of the knob sets different temperature at which the thermostat will disconnect the power supply. So, effectively the hotplates consume same amount of power when ON and only the duty cycle (ON and OFF times) varies when the thermostat setting is changed. So, if we need to use any such hotplate for lower power generation, we need to reduce the supply voltage. As the hotplates are pure resistive elements, their power consumption P_H is given by

$$P_H = V^2/R \qquad \text{........(1)}$$

Where V is the applied voltage and R is the resistance of the heating element. So, any reduction in voltage can reduce the power consumption of the heating element and it is possible to use the same hotplate at 500W or less by reducing the input voltage to the appropriate level. At the same time, a resistive element is insensitive to AC or DC voltage and a hotplate can be readily used in DC voltage system without any modifications.

Based on these facts we chose a hotplate from the market with a brand name 'Osaka' (I am sure it is a China made non-branded hotplate) with a rating of 1000W, 220/230V. Fig.1 shows the picture of the hotplate.

Fig.1. Picture of the hotplate.

While testing in the lab we found that it consumes 1280W at 220V. We applied DC to the hotplate and the results are given below

Table 1. DC voltage measurements of the hotplate

Applied DC Voltage, V	Current, A	Power, W	Comments
230	5.82	1280	
110	2.97	325	
120	3.24	390	
140	3.78	530	

The test data show that we should be using a voltage level that is less than 140V to keep the power consumption less than 500W.

Insulation for the hotplate: The hotplate did not have any insulation at all and the whole structure was simply made of steel sheet with the hotplate heating element placed at the top. So, there was ample scope of heat loss and insulation is needed to reduce heat loss. The possible source of heat loss from the hot plate is the steel frame surface that will get heated and cause heat loss due to convection and radiation. To reduce heat conduction from the hotplate to the bottom surface we packed the hollow space inside the frame with glass wool covered by a fire resistant cloth. Fig.2a shows the picture of the glass wool packed steel frame with the fire resistant cloth attached to the inner surface of the bottom steel plate of the hotplate. The top steel surface is in close proximity to the hotplate and it is not possible to reduce the heat conduction to this plate. So, we took a glass fibre sheet and cut it to the right size such that it covers the top steel surface of the structure but its circular hole at the centre fits the size of the hotplate, as shown in Fig.2b. So, the steel structure is effectively insulated from heat loss but the hotplate portion remains open to get physical contact with the cooking pan.

(a) (b)

Fig.2. a) Glass wool insulation used to fill in the hollow space inside the hotplate frame and a fireproof cloth to prevent glass wool oozing outside the hotplate frame as seen from the inner-back side of the hotplate. b) Fibre glass plate at the top to reduce heat loss from the top surface of the hotplate frame.

2. Induction cooker

There are different induction cookers available in the market with different power ratings ranging from 1600-2000W. All of the induction cookers have options for power adjustment ranging from low values like 100W to the rated power. All the induction cookers available in the market have a voltage rating of 220-240V AC. As the induction cookers electronically generate high frequency magnetic field for induction heating in the steel pans, we expected that the circuits must be running on DC and there should be no problem in using the induction heaters on DC voltages. However, it did not come out to be that simple. We found that there is a thyrister controlled power circuit that converts the supply AC to DC. So, applying DC to the induction cooker makes the thyristers effectively inactive and we face problem in controlling the output power by turning the power control knob. We purchased a 'Walton' induction cooker (locally assembled by a company named Walton) with the following ratings

Walton induction cooker

Model: WI-F 15

Voltage 220-240V AC

Maximum power 1800W

Fig.3. Walton Induction Cooker.

The induction cooker was tested in the lab by applying different DC voltages and putting a steel pan with 1.5 litres of water. Test results are given in Table 2 below.

Table 2. Test results for induction cooker under different input DC voltage.

Applied DC Voltage, V	Power at max. setting, W	Power at min. setting, W	Comment
90			Remains OFF
100	370	280	
120	456	300	
140	546	423	
160	1000	660	
180	1285	727	
Above 185V			Shows over voltage and does not operate

From the test results it is clear that the induction cooker operates on a much smaller voltage range under DC (100-180V). So, we have to use the induction cooker at an appropriate DC voltage to keep the output power to less than 500W. The Table 2 shows that we need to use a voltage less than 150V DC. The built in power control mechanism does not seem to be working effectively under DC voltage as the power variation between the maximum and the minimum setting is quite small. This is probably due to the fact that thyristers lose voltage control capability when DC voltage is applied. So, to control power of the induction cookers under DC voltage applications, we will need to design an external DC voltage regulator that will control the applied voltage to the cooker to control the output power.

3. Water Heater

Two different water heater options were considered for the proposed cooking system. One is a regular water heater (geyser) used in the kitchens or the wash rooms and the other one is a hot water dispenser for coffee or tea. A regular water heater has a larger volume but requires accessories like a tap for water collection and another additional reservoir to replenish the water in the water heater. One the other hand a hot water dispenser, although smaller in size is convenient to use and does not require additional accessories. The picture of the water heaters and their specifications are given below in Fig.4a and Fig.4b.

As a test case we decided to use the hot water dispenser to store hot water for our cooking system. Although the dispenser has a net volume of 6.8 litre, it is possible to get a larger dispenser that will fulfil our storage requirements.

(a) (b)

Fig.4. a) A water heater (geyser) for kitchen or washrooms. b) A hot water dispense for tea or coffee.

We tested the hot water dispenser for their heat retaining capability and found that the outer surface shows significant rise in temperature when the dispenser is energized. We first energized the hot water dispenser close to boiling temperature when the thermostat switches power supply off automatically and then measured the fall in temperature of the water inside with time. The heat loss data is given in the Table3 below.

Table 3. Heat loss measurement data for the hot water dispenser (no additional insulation).

Time, hours	0	1.0	2.0	3.0
Water temp., C	97	90.9	78.3	-

We then insulated the hot water dispenser by covering its outer surface with insulating layers as shown in Fig.5. This time the heat loss was significantly reduced. The heat loss measurement data with the surface insulation is presented in Table 4.

Fig.5. Multiple insulation layers used to reduce heat loss from the hot water dispenser.

Table 4. Heat loss measurement for hot water dispenser (with additional insulation)

Time, hours	0	1.0	2.0	3.0
Water temp., C	97	92.9	88.9	84.9

Although there is marked reduction in the heat loss when additional insulation is added, the temperature still came down to 48C after 24 hours which correspond to 74% heat loss. We intend to reduce it further.

4. Cooking Pans and their insulation

In our cooker design, we plan to use either hotplate or induction cooker where there is no exposed flame. While thinking of designing the insulation for the cooking pans, we tried to choose materials accordingly. We thought of three possible design options. Option 1 was to use cooking pans with glass or some other insulating material side wall and an insulating lid. Such pans usually have a conducting bottom plate to conduct heat from the hotplate or other type of cookers. However, these cooking pans are heavy, inconvenient to use when washing and rinsing in rural environment and are quite expensive, apparently not suitable for rural user in the developing countries like Bangladesh. Fig.6 shows a downloaded picture of ceramic cooking pans.

Fig.6. Ceramic cooking pans.

Option 2 is to use cotton or some other insulating rug strapped on the pan side walls and the lid while cooking. It has the problem of inconvenience of using them and keeping them clean.

Fig.7. Insulating cotton rug strapped on the cooking pan surface.

Optin3 is to use an additional insulated cylindrical pan cover (like an inverted saucepan) that will simply be used to cover the pan while cooking and remove them once the cooking is over. An schematic diagram of the insulated pan cover is shown in Fig.8.

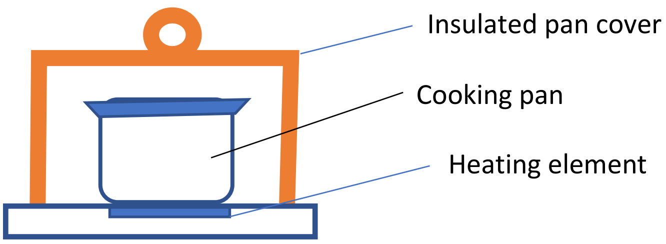
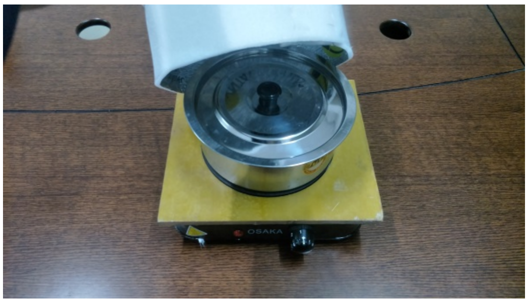


Fig.8. An insulated pan cover to reduce heat loss from the cooking pan.

Such insulated cover can be made quite inexpensive, easy to handle and maintain cleanliness. This is expected to require minimum 'change in habit'. If we can find the insulation materials that can withstand a temperature close to 120°C (like elastometric foam insulator), it can be a good candidate for such a solution.

Considering the simplicity of the design and construction of option 3 (Fig.8), we made an Insulated pan cover from insulation foams as shown in Fig.9.



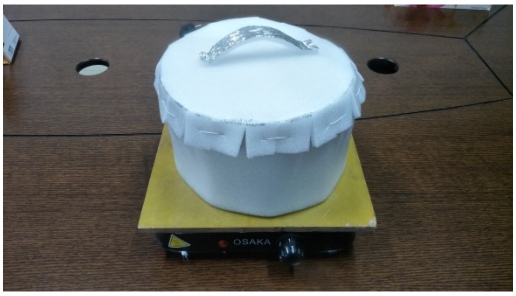


Fig.9. Insulated cooking pan cover.

A heat loss test was performed with and without the insulated pan cover and the results are shown in Table 5.

Table5. Heat loss from cooking pan without and with insulating pane cover.

Time, hours	0	1.0	2.0
Water temp., C (without pan cover)	100	73.9	58.2
Water temperature, C (with pan cover)	100	83	68.5

From Table 5, we can see that the heat retained in the pan is longer. This will ensure lower power requirement while cooking and additional cooking effect even when the cooker is switched off. The data however indicate that there is still scope for improvement. While using the pan cover, we found it very easy to handle and expect that it will not require any significant 'change in habit' for the users.

5. Control Circuit

The control circuit that we propose is effectively a DC link connecting the grid voltage to the PV output. For reduced power consumption of the cookers (hotplate or the induction cooker) we need to apply lower voltage and our experimental data indicate that a 150V DC would be a good choice. As mentioned in the proposal, the water heater will only be consuming power from solar PV and should be connected in such a way that solar PV power will be supplied to the water heater only when there is surplus solar energy or when the cooker is not in operation. So, the basic logic, based on which the control circuit is designed assumes that the solar panel will be operating at 150V under maximum power condition. When PV voltage is 150V or higher, the cooker circuit is switched ON, otherwise remaining OFF. When the PV voltage is more than 155V (it means there is surplus solar power), the hot water circuit is switched ON, otherwise OFF.

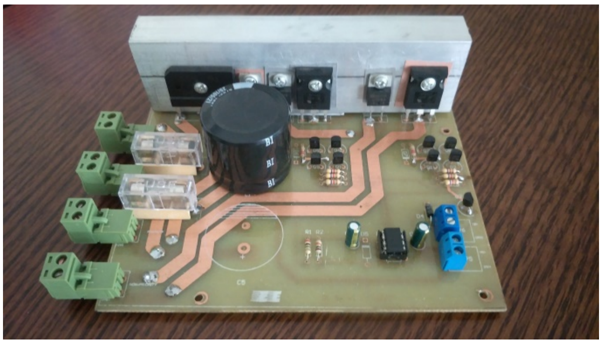


Fig. 10. The control circuit for the solar PV control for optimum operational point.

As the sunshine condition can vary due to variation in weather condition, it is important to operate the solar panel close to the maximum power point and the above logic ensures that. When the solar panel is producing less power than the power required for cooking, the control circuit will go to switching mode to keep the panel end voltage close to the maximum power point. Any additional power required for cooking (when the sunshine is low) will be drawn from the grid via the DC link.

We are still to test the circuit in the laboratory and expect to present the results in the next progress report.

Appendix B: Progress Report 2

Summary : During the report period, we tested our basic idea of cooking solution by power sharing between the grid and the solar PV. An array of 500Wp solar panel (5x100Wp) was installed on the roof top of UIU. Each of the solar panels was designed by a local solar PV assembling company (Omera Solar) to generate 33V at maximum power point. Putting such 5 panels in series generated an open circuit voltage of 205V and a maximum power point voltage of 165V. We used a 600VA, 220/115V transformer to reduce the grid voltage of 220V AC to 115VAC that would produce a peak voltage of 162V. This was necessary for the sake of compatibility of the grid voltage to the voltage of the PV array. As mentioned in the report 1, we chose a system voltage lower than the grid voltage (220V AC) as we observed that off the shelf induction cookers had an operating voltage range of 100-180V while using DC as the input voltage. At the same time, reduced DC voltage reduce the power consumption in all the elements of our cooking solution including hotplate and the storage water heater.

The control circuit that we designed and fabricated has the following characteristics

a) Two different switching schemes were incorporated in the control circuit to control power to the cooker and the storage water heater independently
b) Switch the PV panel ON to deliver power to the cooker when the PV voltage is more than 162V and OFF when the voltage is less than 157V.
c) Switch the PV panel ON to deliver power to the storage water heater when the PV voltage reaches 166V and switch OFF when the PV panel voltage drops to 162. This ensures that the water heater is ON only when there is surplus power in the solar PV.
d) Connect the transformer output to the cooker when the cooker is ON. The connection between the output of the transformer and the cooker is via a full bridge rectifier circuit. So, when the sunshine is strong and the PV voltage is higher than 162V, the diodes prevent power flow from the grid and almost full power is drawn from the PV panel. When the sunshine is less, the PV voltage drops and grid power is delivered to the cooker depending on the voltage level. This ensures optimum/close to optimum operation of the PV panels.
e) Grid output is connected in such a way that grid power never flows to the storage water heater and it consumes power only from solar PV when there is surplus energy.

The grid and the solar PV power sharing data were collected at different hours of the day and the performance of the control circuits design was validated. The measured data are presented in the relevant section of this report.

After attending the Clean Cooking Forum Conference in Nairobi (November 5-6, 2019), it was apparent that pressure cookers will play a major role in the efficient clean cooking solutions. So, we have decided to try pressure cookers in this project, although not included in the original proposal.

Choice of voltage and design of the transformer

As mentioned in the Progress report1, the level of reduced power that we want for our cooking system should is close to 500W and the required voltage level is 160V. So, the first step is to design a transformer that will produce the required voltage level. As we are designing our system for DC output, a 115V AC will produce a peak voltage of 162V. It is a common observation that output voltage drops with load current due to internal impedance of the transformers and we chose to design a 600VA transformer that will reduce the supply of 220V AC to 115V AC. We contacted the local transformer manufacturers and asked them to supply us with the transformer. The picture of the transformer is shown in Fig.1.

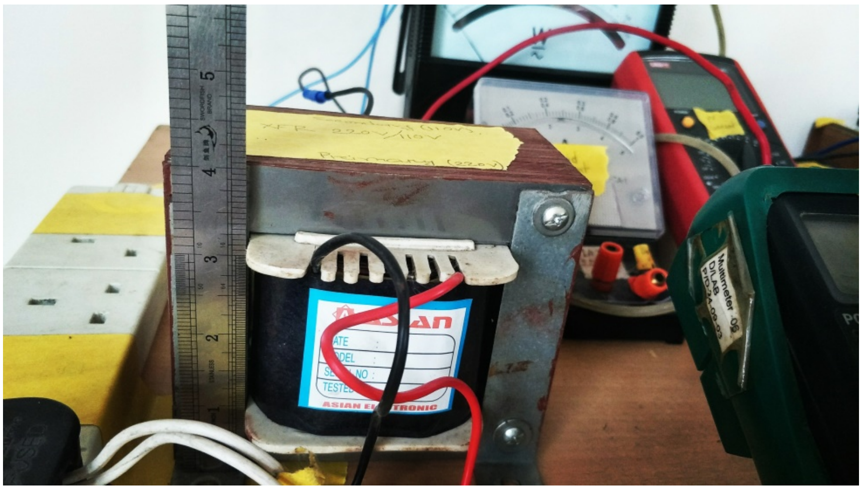


Fig1. The picture of the locally made 220/115 600VA transformer.

The PV array

The usual solar panels available in the market have 36 cells in series and the typical output ratings are as follows

No. of cells in series = 36
Open circuit voltage V_{oc} = 20.5V
Voltage at maximum power V_{max} = 17V

To generate our required 160V, 500Wp at the solar PV panel output we need 10 such panels in series each having 50Wp rating. Smaller sized panels cost higher (per Wp) due to relative longer framing length, larger number of connectors and higher overhead cost. So, we contacted Omera Solar, a local manufacturer of solar panels, to make 100Wp panels suitable for our design. The final design of the individual PV panel of the PV array have the following rating

Power = 100Wp
No. of cells in series = 72
Open circuit voltage V_{oc} = 41V
Short circuit current I_{sc} = 3.3A
Voltage at maximum power V_{max} = 33V

In our design we used 5 such panels in series to generate an open circuit voltage of 205V and the maximum power voltage of 165V. These are close to the values required as per final system design.

The PV framing

While designing the PV framing, we kept the following points into consideration

a) The number of solar panels to be placed in the framing
b) The tilt angle of the framing is such that the panels on an average get the maximum sunshine over a year. The tilt angle is usually taken close to the latitude of the location
c) The structure should be strong enough to withstand stormy weather (quite prevalent in Bangladesh)
d) The structure is securely fixed on the roof so that it is not carried away by strong winds

e) The components of the frame is designed such that it can be easily dismantled and transported
f) Placing the panels in the frame is easy and the frame holds the panels securely

The schematic design of the PV framing is shown in Fig.2.

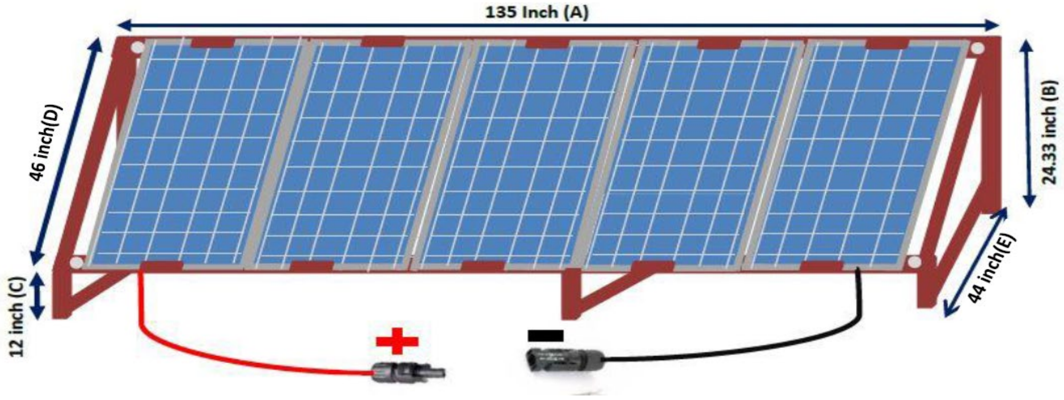


Fig.2. Schematic diagram of PV framing components.

The frame for the PV panel can be dismantled into a box of 30inx56in x12in box and two slender elements of 135in in length so that they can be transported easily from the frame manufacturing workshop to the PV site. The frame is designed in such a way that the PV panels can easily slide into the frame and fixers are used at the ends of the PV array to secure it tightly to the frame. Fig.3 shows that actual picture of the PV panel array placed on the roof top of UIU building.

Fig.3. The PV array setup at the roof top of United International University.

Power Sharing Experiment with Solar PV and Grid

The circuit diagram of the setup is shown in Fig. 4. The PV array and the transformer output are connected via a DC link using full bridge rectifier circuits. The power flow from the PV panels to the cooker and the water heater is controlled by a switching circuit which senses the PV output voltage and switches in such a way that the PV operates close to the maximum power point. This ensures high efficiency operation of the solar panels even under low sunshine condition.

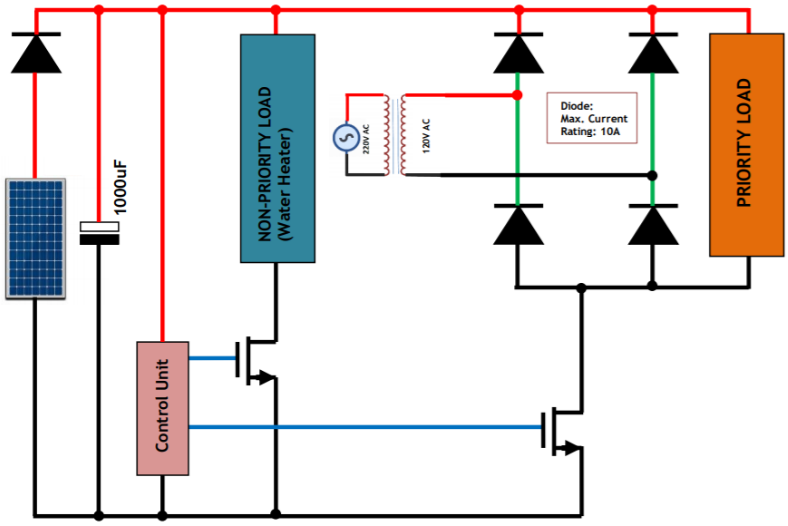


Fig.4. Schematic diagram of the circuit arrangement of the cooking system

The priority load indicated in the diagram is the cooker (hotplate or the induction cooker) and the water heater is shown as the non-priority load. The control unit samples the PV voltage and switches ON and OFF the priority load in such a way that the PV voltage never goes below 155V. However, when the PV voltage exceeds 166V, it means that either there is excess power in PV or the priority load (cooker) is OFF and the control unit switches the non-priority load ON and excess PV power is delivered to it. The non-priority load is switched ON and OFF using a MOSFET in such a way that the PV voltage never goes below 162V.

Fig.5 shows the picture of the actual setup in the lab. A two way switch was used to switch power between the hotplate and the induction cooker. Voltage current and power of the AC side and also on the DC side is measured. In the winter months (October-February) the weather is usually bright and sunny with some infrequent spells of fog and cloud. The readings are taken from 10am to 3pm, as this is the usual cooking time in Bangladesh. The sunshine remains quite significant after 9am and remains high till 2pm. However, the sunshine diminishes rapidly after 3pm and so is the PV power production.

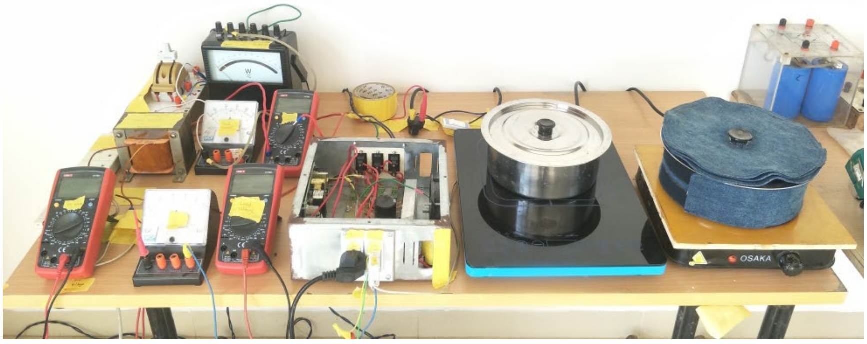


Fig.5. The picture of the laboratory setup with hotplate and the induction cooker connected to the 500Wp solar PV at the roof top and the grid supply.

The proposed cooking system was set up in the lab to see the performance of the system and obtain practical data on the power sharing between the solar panels and the grid. In the set up, we independently used hotplate and the induction cooker under different sunshine condition. The storage water heater was connected to the system so that the water is preheated before the cooking starts at 10am. The water heater was loaded with fresh water at room temperature every evening and increase in water temperature was noted at 10am every morning. It may be mentioned here that the control circuit is designed such that the power from solar PV is delivered to the water heater only when there is a surplus of PV power. This ensured by sensing the PV output voltage. When the load on the PV is decreased the ususal I-V characteristics show that the PV voltage keeps on rising. We exploited this voltage change to estimate excess power in the PV output. Before 10am in the morning, no cooking was done and the water heater gets full PV power to preheat the water. The storage water heater data is presented in Table 1.

Table1. Temperature rise in the water heat at 10am in the morning before starting cooking in the system

Miyako water heater, 4.5L capacity			
Date	Temp. at 4.30pm (the previous day)	Temp. at 10am	Remarks
25.11.19	31.8	89.3	Slightly cloudy
26.11.19	29.0	97.3	Sunny
1.12.19	27	92.3	Sunny
3.12.19	26.5	97.2	Sunny

It is interesting to see that the temperature in the water heater rises close to boiling by the time cooking starts at 10am. This indicates that the temperature of the water heater becomes high enough to be effectively used for cooking. It also indicates that excess PV energy stored in the form of hot water can be quite effective if the right volume of water heater can be chosen.

While testing for power sharing, we did not cook any food, but took the data with 1.5L of water in a cooking pot. Table 2 shows the hotplate power sharing data for between the solar PV and the grid at different time of the day so that we can observe significant variation in sunshine.

Table 2. Power sharing between the solar panel and the grid when the hotplate is used as the cooker

Date	Time, hrs	PV voltage	Power from PV	Power from grid	%PV power	Remarks
26.11.19	10.20 AM	155	365.8	251	59.3061	Sunny
	11.00 AM	157	353.25	290	54.91644	
	12.00 PM	152	369.36	245	60.1211	
	1.00 PM	159	329.13	325	50.31569	
	2.00 PM	155	274.35	350	43.9417	
	3.00 PM	148	211.64	365	36.70228	

27.11.19	10.20 AM	170	342.93	360	48.7858	Sunny
	11.00 AM	171	369.60	335	52.45529	
	12.00 PM	170	323.61	357	47.54705	
	1.00 PM	163	335.78	355	48.60882	
	2.00 PM	151	238.58	355	40.1934	
	3.00 PM	148	219.04	370	37.18593	

We used parallel setups for the hotplate and the induction cooker so that simultaneous data could be collected for both the cookers. Table 3 shows the power sharing data for the induction cooker.

Table 3. Power sharing data for induction cooker

Date	Time, hrs	PV voltage	Power from PV	Power from grid	%PV power	Remarks
26.11.19	10.02 AM	157	379.94	223	63.01456	Sunny
	11.02 AM	155	348.75	265	51.24679	
	12.02 PM	157	376.8	225	50.69091	
	1.02 PM	157	324.99	315	52.33556	
	2.02 PM	158	274.92	285	44.46912	
	3.02 PM	150	211.5	315	39.81428	
27.11.19	10.02 AM	170	343.4	240	58.86184	Sunny
	11.02 AM	171	357.39	340	51.24679	
	12.02 PM	170	348.5	339	50.69091	
	1.02 PM	168	307.44	280	52.33556	
	2.02 PM	154	240.24	300	44.46912	
	3.02 PM	151	208.38	315	39.81428	

The circuit configuration as shown in Fig. 4 is designed in such a way that the PV voltage will follow the grid voltage. In Bangladesh the grid voltage varies from 220-230V AC and we can see that the PV voltage in the above tables shows some variation, which has occurred due to the variation in grid voltage (compare the PV voltage at 10am and 3pm on 27.11.2019). The power output of the PV was found to be quite significant and the power sharing between the PV and the grid had been smooth without any technical hitches. If we look at the percentage share of the PV, it does not exceed 60%. This is mainly due to the fact that both the hotplate and the induction cooker had been consuming close to 600W although we expected to achieve less than 500W. So, we plan to purchase low power cookers (to be imported from China) so that the actual power consumption remains lower than the 500W. Under such a circumstance, the share of solar PV, on an average, will remain above 70%.

Appendix C: Progress Report 3

Summary: During this period we tested our appliances by cooking foods using the system we developed, as reported in Progress Report 2. The details of the cooking process is reported in the later part. As we used the system voltage close to 160V, we had to use a transformer to step down the grid voltage to the required level. While using the circuit, it seemed that the transformer is the single most heavy and voluminous component of the control circuit, so we thought of redesigning the system eliminating the transformer by using Pulse Width Modulation technique on the DC side of the grid supply. As already mentioned, we do not need 1000W power for cooking as we used insulated pan cover to prevent heat loss. So, we searched the local market for hotplate and electric pressure cooker that consumes less than 500W and could not find one. So, searched ON LINE in the international market like Alibaba and found some appliances that fit our requirements. We ordered one hotplate having a power rating of 500W and an electric pressure cooker having a power rating of 600W through a local delivery agency. The expected date of delivery was 3rd week of December but unfortunately the local delivery agency could not delivery them in time and also could not provide any specific date for the delivery. On the other hand, the new designed circuit that eliminates transformer was also sent to China for the printed circuit board and the delivery got delayed. Anticipating delay in our final version of the circuits, we requested for time extension till March 23, 2020 and it was approved. In the mean time, outbreak of corona virus affected the local and the international market when China declared a lock down. So, we neither got the right circuit components nor the right appliances. So, looked in the local market for AC-DC converters that can convert the grid AC to fixed output DC and found some which re used as LED drivers. We used a combination of them that can generate an output DC voltage within a range of 120-140V. We chose a DC voltage of 126V, a voltage that keeps the power of the appliances that we used lower than 500W (usually these appliances have a rating 900-1800W at 220V AC). Modification of the output DC voltage required change in the output of the PV array and we reduced the number of panels in the array from 5 to 4. This reduced the power capacity of the panels but kept them at a voltage close to their maximum power point.

In the final stage, we used a pyranometer to compare the PV power output to the sunshine and found that the power extraction from the PV was close to 90%.

Rice cooking test:

In this phase of the experiment we cooked rice, amount of rice is 0.5 kg and water added was 1.5L. The test was performed with hotplate and the induction cooker with and without the insulated pan cover. In both the cases we kept the power supply to the appliance ON till the water started boiling and then switched it OFF and left the pan for natural cooling. The rice was checked for its quality of cooking 30 minutes after the power was switched off. The results are shown in Table 1 below.

Table 1. Rice cooking data.

Cooker	Insulating cover	Initial temp.	Time ON	Time OFF	Grid Energy, kWh	**PV energy, kWh**	Total energy, kWh
Hotplate	**No**	**26.2**	**10.25am**	**10.45am**	**0.17**	**0.09**	**0.26**
Hotplate	**Yes**	**17.8**	**3.40pm**	**4.10pm**	**0.24**	**0**	**0.24**
Induction cooker	**No**	**19**	**10.20am**	**12.41am**	**0.14**	**0.05**	**0.19**
Induction cooker	**Yes**	**20.2**	**1.33pm**	**1.53pm**	**0.18**	**0.0**	**0.18**

The energy consumption does not shown any significant change when the insulated pan cover is used. It seemed to us that the rice cooking was a quick process and it did not take very long time to reach 100C. Actual loss mechanism accelerates once the temperature of the pan gets high (close to 100C).

(a) (b) (c)

Fig.1. Experimental setup for the rice cooking. (a) Hotplate without insulating cover (b) Hotplate with insulating cover (c) cooked rice.

Next we chose chick peas as the next item for cooking. The process of cooking chick peas require pre-soaking of the peas for more than an hour and then put them on the cooker for cooking. The usual cooking time for the chick pea is quite long and we expected that insulating cover will show significant energy saving in this case. The day we performed this experiment, it was a cold and very gloomy weather with very low level of sunshine. So, we decided to perform this experiment with usual grid power of 220V AC. The results are presented in Table 2.

Table 2. Chick pea cooking measurement data. As the sunshine was very low, we used the usual grid voltage of 220V AC for this experiment and the power consumption was 1180W.

Cooker	Insulating cover	Initial temp.	Time ON	Time OFF	Grid Energy	**PV energy, kWh**	Total energy, kWh	
Hotplate	**No**	**22.8**	**10.00am**	**11.06am**	**1.03**	**0**	**1.03**	
Hotplate	**Yes**	**22.0**	**2.31pm**	**3.01*pm**	**0.6**	**0**	**0.6**	

*The pan was kept insulated till 4.25pm to have the additional cooking effect even after the power is switched off.

Fig.2. Chick peas cooked on a hotplate.

This time we found that there was significant reduction in energy consumption when the insulating pan cover was used. We also found that the induction cooker glass plate (where the cooking pan is placed) did dissipate heat as the cooking pan cooled down quicker even when the insulating pan cover was used. We also measured the temperature of the bottom surface of the induction cooker and found that it was quite high (76C).

Electric pressure cooker: Cooking of chick pea
A very simple low cost electric pressure cooker (cost~ GBP 40) was bought from the local market. Rating of the pressure cooker is given below

Brand: Sinbo (Made in China)
Voltage: 220V
Power: 900W

Fig.3. The Sinbo brand electric pressure cooker

The electric pressure cooker did not have any temperature control or any other control other than a timer that switches OFF the cooker when the time is over. In case the timer is set high and the pressure inside the cooker exceeds the limit of the valve, we could see the escaping steam through the valve. We used 250gm of chick peas (pre soaked) and 1.5L of water. The electric pressure cooker, when connected to the PV system of 162V, the actual power drawn by the 900W pressure cooker was 390W. The experimental results are presented in Table 4.

Table 4. Electric pressure cooker test with 250gm chick pea and 1.5L of water. Power consumption is of the electric pressure cooker was 390W.

Cooker	Insulating cover	Initial temp., C	Time ON	Time OFF	Grid Energy, kWh	**PV energy, kWh**	Total energy, kWh	
Electric pressure Cooker	**No**	**19.2**	**1.02pm**	**1.35pm**	**0.06**	**.15**	**0.21**	

Fig.4. Chick peas cooked using electric pressure cooker.

While cooking, we found that the pressure cooker side walls were mildly heated, but the lid became very hot and the temperature rose up to 90C. So, it seems that the lid is a possible source of loss in this pressure cooker. However, as the actual cooking time was low, the heat loss might not be too high. Compiled chick pea cooking data from Tables 4 and 5 is presented in Table 5.

Table 5. Compiled chick pea cooking energy data from Tables 4 and 5. Chick 250gm, water 1.5L

Energy consumption, Hotplate without insulating cover, kWh	Energy consumption, hotplate with insulating cover, kWh	Energy consumption, Electric pressure cooker, kWh	
1.03	0.6	0.21	

It is interesting to see that with electric pressure cooker there is 5 times energy saving when compared to hotplate energy without insulating cover and almost 3 times energy saving compared to hotplate data with insulating cover. In case of pressure cooker there is no significant water loss and 1.0L of water (instead of 1.5L) is enough to cook chickpeas. A simplified calculation shows that the energy requirement would be 0.16kWh, if 1.0L of water is used. Such energy savings are possible by using reduced amount of water with other dishes, particularly when longer cooking time is needed (like cooking beef).

The PV array

As mentioned in the earlier reports that the PV array that we used was designed to have an output DC voltage of 162V. This voltage was chosen to operate the higher power rated cookers to operate at a lower power and we successfully demonstrated it by running hotplate and induction cooker. However, this design requires to reduce the grid voltage of 220V AC using a transformer to make the voltage level compatible with the PV voltage on the DC side. The transformer was heavy (close to 3kg) and occupied 40% of the total volume of the control circuit. So, we decided to make a new design of the control circuit that will operate without a transformer. This time, to match the grid voltage we had to change the PV array design to make its voltage level compatible with the grid voltage. So, we designed and installed a new PV array having the following rating of the PV panels

Brand	
Power rating	30Wp
Open circuit voltage	21V
Short circuit current	1.96 A
Maximum power voltage	17V
Maximum power current	1.76 A

Fig.5. New PV array setup at the roof of UIU

As the peak voltage of a 220V AC supply is 310V, we connected 20 such PV panels in series to reach close to the grid peak voltage. The picture of the newly installed PV array is shown in Fig.5.

With this setup, the open circuit voltage is 420V and the maximum power point voltage is 340V. The maximum power point voltage is intentionally chosen higher than 310V so that operating point remains close to the optimum point even when the grid AC voltage fluctuates to high values like 240V (corresponding to the peak value of 338V). The performance of the newly installed PV array with our new proposed control system could not be tested as we did not get timely delivery of the control circuit that we designed for this new array. We will include the test results on the performance of the panel and the control circuit in the final report.

AC-DC converter to replace the transformer inside the control circuit

Outbreak of corona virus resulted in the unavailability of the electronic components and the cooking appliances we had been looking for (appliances having power rating less than 500W). So, we decided to go ahead with the components available in the market. Searching the market, we found that some AC-DC converters were available in the local market, the prices and the ratings are given below

1. 220V AC to 24V DC, 10A - GBP 8
2. 220V AC to 48V DC, 10 A - GBP 18
3. 220V AC to 60V DC, 10 A - GBP 30

All the AC-DC converters had an adjustable potentiometer so that the voltage could be varied by ±10%. Ideally, a 220V AC to 130-140V DC converter would have been the best, but we could not get any such converter in the market. So, we decided to connect them in series at the output to get the voltage that we need. We connected all these three to generate an output DC voltage of 120-140V and chose to use a DC voltage of 126V. The choice was made to make sure that all our cooking appliances take less than 500W at the chosen voltage level (at 126V DC hotplate, induction cooker and the electric pressure cooker consumed 482W, 485 and 328W respectively).

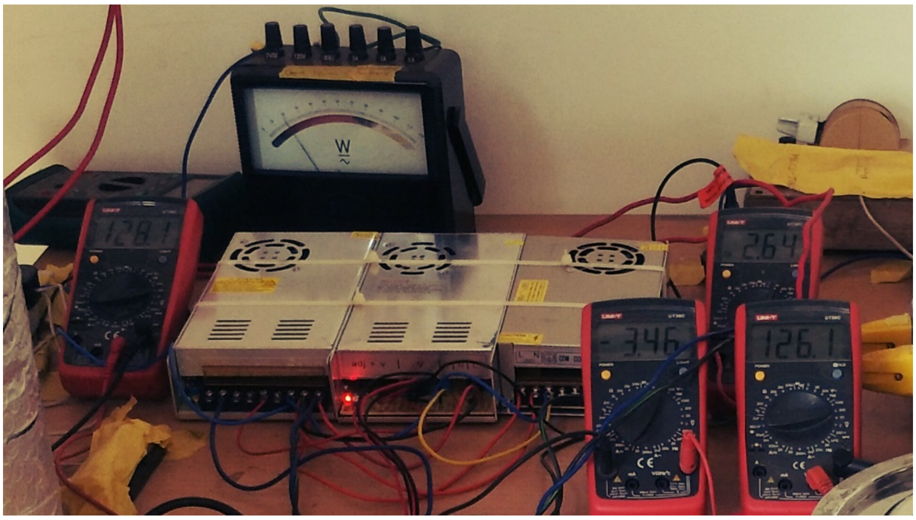


Fig.6. Three AC-DC converter connected in series at the output to generate a load voltage of 126V DC.

Modification in the PV array

As the operating voltage of the cooking appliances were reduced to 126V DC, we decided to reduce the voltage of the PV array. Earlier, we used two PV arrays in our setup, one using five 100Wp panels generating a maximum power point voltage of 170V and the other having twenty 30Wp panels to generate a maximum power point voltage of 340V. Considering the voltage level of the AC-DC converter, we decided to use the first array with five 100Wp panels. As the difference between the operating DC voltage of 126V and the maximum power point voltage of 170V was too big, we decided to reduce the PV array to four 100Wp panels and the maximum power point voltage becomes 135V. This ensures the operation of the panels closer to maximum power point, although this reduced the power capacity of the PV array.

Fig.7. Modified PV array with four 100Wp PV arrays connected in series to generate the maximum power point at 135V DC.

Sunshine measurement and comparison of PV power output

A Pyranometer was used to measure the income sunshine on the PV array by placing it in parallel with the plane of the array. The setup is shown in Fig.7.

Fig.7. Pyranometer setup for the measurement of sunshine.

The pyranometer reading and the corresponding PV power output to the cooking appliance was measured under different sunshine conditions to see the actual power output from the PV. The results are presented in Table 6 with hotplate as the load.

Table 6. Incident sunshine in relation to the output power of the PV array. The load voltage was fixed at 126V DC.

Time, hrs	Solar radiation	Generation at PV, W	Actual PV output, W	%PV output extraction	Output from grid, W	Total power, W
10.3	892.5	357	312	87.4	122.7	434.7
12	795	318	291	91.5	143.7	434.7
14	757.5	303	273	90.1	161.7	434.7

The actual power extraction was quite high, close to 90%. The losses included the loss in the power cable (2.5%) connecting the PV array at the roof top to the lab (a distance close to 20m), loss in the control circuit (3%) and some loss due to deviation of the load voltage from the maximum power point voltage (4.5%). Please note that the maximum power point voltage is 135V whereas the operating voltage is 126V.