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A Solar PV-Based Inverter-Less Grid-Integrated Cooking Solution for Low-Cost Clean Cooking

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Abstract: The cost of solar PV has been reduced to a level such that the levelized cost of solar electricity is either cheaper or competitive relative to the grid electricity. So, a low-cost integration of solar PV with grid can be a cost-effective solution for clean cooking. The usual technique of using grid-tied inverters contribute ~20% towards the energy cost. The proposed system incorporates a control circuit that connects grid electricity to the solar PV via a DC link and provides a DC output eliminating the requirement of grid-tied inverters. Most of the cooking utensils either have a resistive heating element or an electronic control circuit that is insensitive to input AC or DC and no modification is needed for the cooking utensils while using with DC voltage. In the proposed system, preference for power delivery is always given to the solar PV and the grid effectively operates as the backup for the system when solar PV output fluctuates due to varying weather and climatic conditions. As the absence of a grid-tied inverter in the system restricts the excess solar energy to be transferred to the grid, some kind of energy storage device is essential to run the system efficiently. A novel idea of storing solar PV energy in the form of hot water has been presented in this paper, with a cost-effective clean cooking concept. A simple and low-cost heat preservation technique has been suggested that requires a minimal change in habit for the users. Experimental results with multiple cooking utensils and foods have been presented and energy cost for cooking has been found to be as low as 4.75 USD/month, which is significantly lower (32%) than that of the grid-connected regular cooking system.

Keywords: clean cooking; solar PV; hot water storage; grid-tied inverter; DC-based cooking; energy efficiency

1. Introduction

Despite the positive trend in the economic growth of the less developed Asian and African countries, more than half of the world population still uses biomass [1–4] and are subject to health hazards from the toxic fumes and suspended particles from the stoves [5–10]. An apparent low-cost solution of biomass stoves ultimately gives rise to health issues [10] and the hidden cost can be quite significant [10–12]. Although the SDG7 sets the goal for affordable and clean energy, development of a low-cost clean cooking technology is still a challenge. An affordable low-cost clean cooking technology has a number of impacts that can have global implications such as a reduction in GHG emission, improvement in the quality of life at the bottom of the pyramid, and mitigation of gender discrimination against women [13] that are mostly affected by lack of kitchen hygiene and contribute in poverty alleviation due to lower cooking cost and reduced health hazards.

The main challenge for clean cooking in the developing world is the cost of cooking, with two main components—the hardware cost and the energy cost. There may be limitations on the availability of cooking resources in certain geographical locations, but such unavailability of resources is ultimately reflected in the cost. Under-privileged people in the developing countries predominantly use charcoal or biomass due to their relative low cost, neglecting the underlying health-related costs due to toxic emission. Gas cookers, although they may not have the same high efficiency as an electric cooker, are more efficient compared to the conventional stoves but still pose health threats [14–16] and are relatively expensive. With the progress in the implementation of the Sustainable Development Goals (SDG) electric cooking seems to be the ultimate option for clean cooking. In electric cooking, the energy cost of cooking is heavily dependent on the cooking efficiency, either the efficiency of the appliances or of the cooking process. Ravindranath and Ramakrishnan [17], Cowan [18] and Leach and Oduro [19] studied the energy consumption in different cooking appliances including electric appliances. The experimental data show that electric cooking consumes much less energy compared to other cooking fuels. A good number of studies have been conducted where researchers propose electric cooking as a clean affordable option including the solar PV with battery backups [19–27] in off-grid areas. In all the studies incorporating battery with solar PV, the battery is the single most expensive component while estimating the levelized cost of energy. So, identifying the cooking losses [28–31] and enhancing efficiency of the cooking appliances and the cooking process seems to be an essential element to make electric cooking economically attractive. A recent study shows that using electricity with the adoption of appropriate loss reduction mechanisms, it is possible to cook using less than 500 W [32] 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.

The paper also indicates that electric cooking could be an attractive solution in grid-connected areas if the cooking cost can be reduced by enhanced cooking efficiency. Cost of cooking includes the cost of the hard wares/appliances and the cost of cooking energy. One of the challenges that electric cooking faces is the relatively high energy requirement for cooking. In many of the developing countries, if electric cooking in the households become popular, it may overload the existing power lines. So, 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. This opens up an opportunity to consider integration of solar PV in electric cooking even in the grid-connected areas. If roof top PVs can be used via some innovative circuitry avoiding grid-tied inverters with the grid as the backup instead of a battery, it is possible to locally generate low-cost electricity that can supplement the grid. This will reduce the overall electricity cost (eliminating the inverter can reduce the PV electricity cost by around 20%) and at the same time reduce the challenge of transmission lines being overloaded.

2. Our Proposition and the Methodology

In this research, we identify the cost of clean energy and its accessories as the main hurdle towards adopting clean cooking technologies. Here we propose a low-cost grid-connected solar PV-based cooking solution with specific emphasis on the following aspects:

- Inverter-less integration of solar PV with cooking system in the grid-connected area for lower cost and increased efficiency.
- Enhancing cooking efficiency to reduce energy consumption by insulating the cooking pans.
- Storing of surplus energy from the solar PV in the form of water heating, with the hot water to be used for cooking. This eliminates the battery or any other more expensive energy storage element.

The methodology adopted was as follows:

- We used appliances and materials readily available in the market, so that the minimum modifications are needed in adopting the system.
- To achieve the lower power consumption of the cooking appliances and low-cost integration with solar PV, we modified the voltage level and the type of voltage supply (DC in our case) using a control circuit to match our scheme.

- Performance verification of all the cooking appliances under the modified voltage supply was done before performing the actual cooking data collection.
- Cooking performance of the system was evaluated experimentally with and without hot water from the water heater to see how much energy saving was achieved.
- Power and energy share from the PV was monitored in each experiment to get an estimate of the energy share of the PV under an average sunshine condition.

While implementing the abovementioned features, care is taken to introduce a minimum "change in habit" so the users do not find it difficult to adopt in different cooking cultures or geographical locations.

3. The System Description: Inverter-Less Integration of PV with Grid-Connected Cooking System

This research aims to maximize the use of solar PV, which has become quite inexpensive in recent years. While using PV as an energy source for cooking, we face two major difficulties—first is the reliability of sunshine and second is the utilization of the PV energy when the cooker is not in use. In grid-connected areas, it is a common practice to connect the solar PV to the grid via a grid-tied inverter, so that excess power from the PV is delivered to the grid so long as the grid power does not fail. In case of small sized grid-tied inverters less than 1 kW, the cost of the grid-tied inverters is high enough (cost of a small grid-tied inverter is a ~USD 150) to make the solar PV energy cost less attractive compared to the cost of grid energy. So, in grid-connected areas, cooking with solar PV-based electricity is not a popular solution yet. In this research, the main innovation lies in the design of the control circuit that will eliminate the use of an inverter and use the 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 (cost of water heater is ~USD 20). The water heater will store the energy in the form of heat so that the hot water can be used for cooking. 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 connects the solar PV on the DC side. Both the electric cooker and the water heater operates on DC voltage. In the proposed design, the number of solar panels to be connected is determined by the system design that includes the power requirement from the solar PV and the operating DC voltage. A schematic diagram of the proposed system is shown in Figure 1.

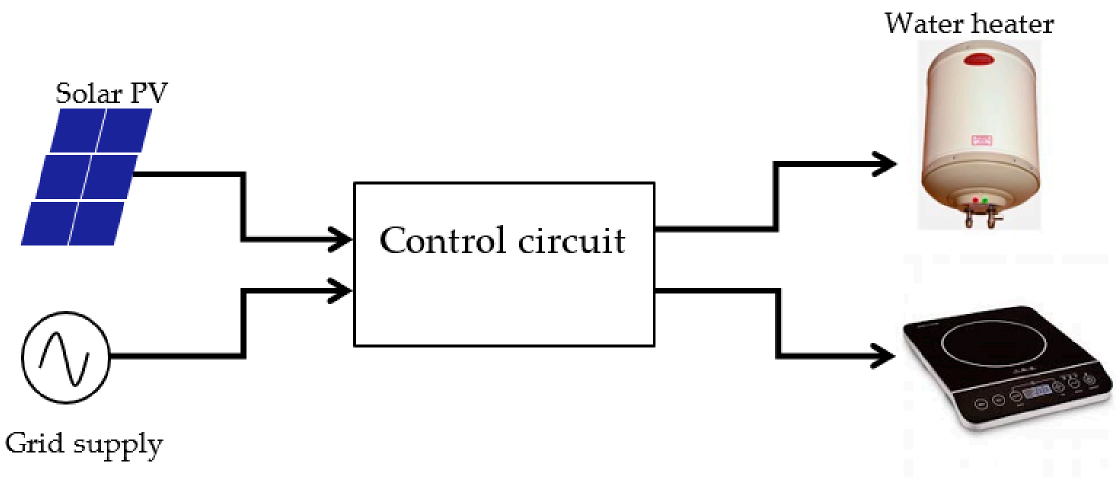

Figure 1. The block diagram for the proposed cooking system.

4. The System

4.1. Choice of the Cooking Appliances and the Load Side Voltage

In our research, we decided not to make any modifications on the cooking appliances that are available in the market and use them as they are. This was to ensure that the users could simply buy a cooking appliance from the market and just plug it in to our proposed cooking system. However, the power ratings of the cooking appliances available in the market are much higher than those needed in our cooking system (less than 500 W), as presented in Table 1, which made us choose a lower voltage at the appliance end. Table 1 shows that we can reduce the power consumption, without introducing any modification in the appliances, by reducing the input voltage only.

Table 1. Power consumptions of different cooking appliances at different voltage levels.

Appliance Tested	Hotplate	Induction Cooker	Electric Pressure Cooker	Water Heater (Cap. 6 L)
Rating	1200 W 220 V_{AC}	1800 W 230 V_{AC}	900 W 220 V_{AC}	900 W 220 V_{AC}
Power at 120 V DC	372 W	456 W	272 W	276 W
Power at 130 V DC	432 W	488 W	321 W	325 W
Power at 140 V DC	514 W	546 W	367 W	376 W

4.2. System Voltage

Choice of the system voltage (DC voltage) is the most critical element as it needs to ensure two basic criteria. First, the voltage should be such that the PV array operates close to its maximum power point when connected to the system. Second, the power consumption of the cooking appliances under the chosen DC voltage should remain lower than 500 W. We have already mentioned that it is possible to cook consuming less than 500 W.

While studying the behavior of the cooking appliances under DC voltage condition, as presented in Table 1, we found that all the AC-rated cooking appliances do work well with DC voltage. It is not an unexpected outcome as most of the cooking appliances have resistive heating elements except for the induction cookers. The electronics used inside an induction cooker operate over a wide range of voltage and basically use DC inside the appliance by rectifying the AC supply. It was found that the appliances (including the induction cooker) while tested in the lab, as presented in Table 1, consume less than or close to 500 W over a DC voltage range of 125–140 V. It is our understanding that application of DC voltage does not have any long term adverse effect, as heating is the dominant effect inside a cooking appliance. Lower voltage means less heating (as can be seen from Table 1) and any chance of overheating is virtually absent. However, further study will be needed to substantiate the claim. When looking at the solar PV panels available in the market, we found that the commonly available panels have 36 cells in series with an open circuit voltage of 21–22 V and the maximum power point at 16.5–17.5 V under the standard testing conditions. This means that we can connect 8 such panels in series to obtain a maximum power point voltage of 132–140 V, which closely matches with our voltage and power requirement for the cooking appliances. It is also worth mentioning that the maximum power point voltage reduces with reduced sunshine. So, we decided to choose 130 V DC as our system voltage that fulfills both the criteria for cooking power less than 500 W and optimum operation of the PV array.

4.3. Solar-PV Panels

As already discussed, at the load end, DC voltage of 130 V was chosen and the PV array was designed accordingly. Instead of using 8 solar panels in series, 4 solar panels (multi-crystalline) with 72 cell PV panels have been used in series each having a power of 100 Wp. The panels were assembled by one of the local manufacturers (Omera Solar, Radiant Alliance Limited, http:

//www.ecg.com.bd/business-services/radiant-alliance-limited/). Solar panels of 100 Wp were chosen to have a fewer number of panels in the array to make the framing of the panel array structure simpler. The ratings are given in a Table 2.

Table 2. Solar PV (100 Wp) data.

Power, W_p	No. of Cells in Series	Open Circuit Voltage, V	Short Circuit Current I_{sc}	Voltage at Maximum Power V_{max}
100	72	41 V	3.3 A	33 V

The solar panel array was placed on the roof top of the United International University, Dhaka, Bangladesh. They were made south facing having an elevation angle of 20° (the latitude of Dhaka is 23° N).

4.4. The Control Circuit

The schematic of the cooking system is shown in Figure 2. On the grid side, an AC to DC converter is used that converts the grid AC of 220 V to 130 V DC (as per our design). As we do not expect the cooking appliance to consume more than 500 W, the AC to DC converter does not require a current rating of more than 5 A. A 1000-µF, 400-V capacitor was connected in parallel to the PV panel output to ensure efficient utilization of PV energy when PV output is subjected to switching mode operation (with the water heater). The solar PV array and the AC-DC converter output are connected to the DC bus via a diode so that both of them are protected from the backward flow of power. The water heater that stores excess energy in the form of heat, is connected in such a way that it draws energy from PV only. The power switch (MOSFET) that controls the water heater power flow is switched ON when the PV voltage reaches 135 V and is switched OFF when the voltage goes below 132 V. Effectively, this operates in a switching mode as the PV voltage goes higher when the cooking appliance is not in use or the sunshine is high to generate more power than the power required by the cooking appliance. The PV voltage sensor circuit senses the PV array output voltage and makes the power control switch of the water heater ON or OFF as per the logic mentioned above. The capacitor connected in parallel to the PV panels acts like a momentary storage of the PV power when the system goes to switch mode operation for the water heater. This ensures efficient operation of the PV panels.

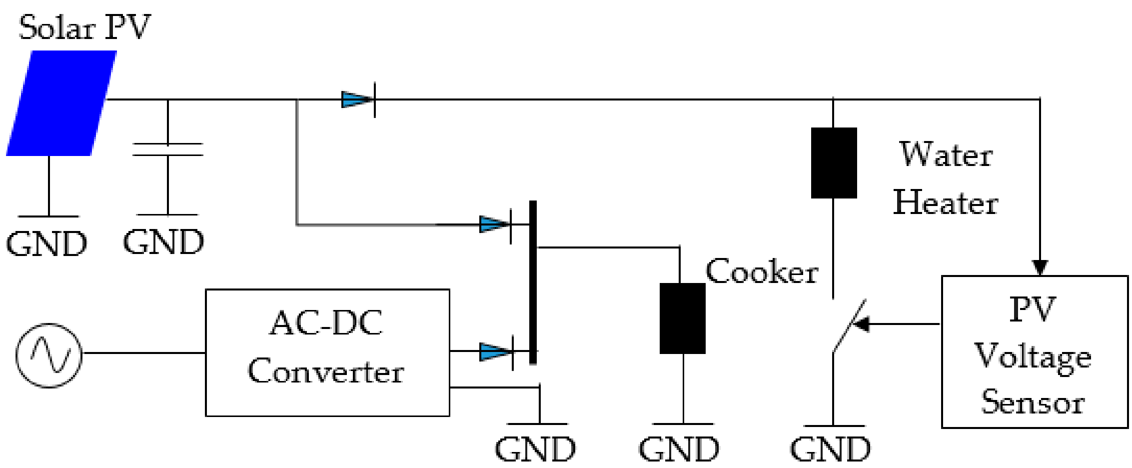

Figure 2. Schematic diagram of the cooking system.

4.5. The Water Heater

Water heaters usually use resistive heating elements and are insensitive to AC or DC supply. We have chosen a water heater of 6-L capacity having a rating of 220 VAC, 900 W. The capacity of the water heater chosen was based on the size readily available in the local market. Under the proposed 130 V DC, the water heater consumed 325 W (Table 1). The actual amount of water requirement depends on the type of food and process of cooking. However, a 6-L water heater should be sufficient for a family of 4 members in the context of Bangladesh.

4.6. Insulated Pan Cover for Heat Retention

The surface area of the cooking pans is a major source of heat loss in conventional cooking processes. It is important to realize that "heat does not cook, it is the temperature that cooks" meaning that the cooking process is affected by the temperature retention not by the actual amount of heat that is supplied to the pans. If a high level of heat retention can be achieved in a cooking process, it is possible to cook with a very low amount of energy. Non-insulated cooking pans usually have a metallic body and they radiate a significant amount of heat energy during and after cooking. If an insulated pan cover is used, it can retain heat inside the cooking pan for a longer time and the cooking effectively continues even when the cooker is switched off. There can be significant energy saving by insulating the cooking pans and our low-cost and simple insulated pan cover was designed as shown in Figure 3.

Figure 3. Schematic diagram and pictures of insulated pan covers for the cooking pans.

Insulated pan covers were made from 1-cm-thick polystyrene foam, the materials used for ceiling insulation when people insulate galvanized iron sheet roofs. As there is no open flame in electric cooking, we found them to be safe while using with the electric cookers. Any insulating material that can withstand the temperature generated in the cooker should work fine. Thicker insulation will reduce the heat loss no doubt, but it will increase the volume and cost of the pan cover and may cause inconvenience for the users. However, if any of the users find it inconvenient, they have the option not to use it by paying the price for the extra cooking energy.

5. Results

5.1. Power Sharing between the Grid and the PV Panel

After the system was connected, as shown in Figure 2, with the load end voltage setting at 130 VDC, first the hotplate was connected as the cooking appliance to observe the power sharing between the grid and the PV under different sunshine conditions. A pyranometer was placed in parallel with the solar panels and the incident sunshine was measured. Corresponding PV power data were collected on a bright sunny day to see the power sharing between the PV and the grid under different sunshine conditions. In Table 3 below, we have included the expected output power from the PV panel under the given sunshine condition calculated from the sunshine data. If, S is the sunshine in watt/m^2, and W_P is the watt peak rating of the panel, then the expected power generation in the panel is

$$\langle W \rangle = W_P * S/1000 \quad (1)$$

Table 3. Experimental data of power extraction from the PV and the power sharing with the grid. The voltage at the load end was 131 V_{DC} and a hotplate was used as the load.

Time, h	Solar Radiation on Panels, W/m^2	Expected Solar Power, <W>, Watt	Actual PV Output, W Watt	% PV Output Extraction, η_{pe}	Energy from Grid, Watt	Total Power, Watt	%PV Share of the Total Power
10.30 a.m.	865.5	346	312	90.17	122.5	434.5	71.7
12.00 p.m.	795	318	291	91.5	143.2	434.2	66.9
14.00 p.m.	757.5	303	273	90.1	161.0	434.0	62.6

However, we do not expect to extract 100% of the generated power as there are losses. If W is the actual power output from the panel then the power extraction efficiency η_{pe} is given by

$$\eta_{pe} = W/\langle W \rangle \quad (2)$$

This gives us an idea about the losses in the energy extraction process as there are losses in the panels like partial shading, dust accumulation, line loss etc. Besides, as we do not track maximum power point but keep a system voltage close to the maximum power point. So, we would expect some losses due to variation of the maximum power point voltage under varying sunshine conditions. The experimental data on power extraction from the PV panels are given in Table 3, with a hotplate as the load.

Bangladesh has an average sunshine level of ~4.5 kWh/m^2/day [33] on a horizontal surface and we expect an average power output of ~250 W from the 400-W_P panel tilted 20° to the south when cooking is done between 10.00 a.m. and 14.00 p.m. For a cooking power of 450 W, this would correspond to ≈56% share of solar power. This power sharing can be made higher with higher capacity solar panels, but that will require higher storage capacity for the water heater to store energy during non-cooking hours and will also increase the cost of the system.

5.2. The Water Heater

Water heater data were collected by filling up the 6-L water heater in the evening (when there is no sunshine) using tap water at room temperature (varying from 19 to 30 °C depending upon the ambient temperature) and the water heater temperature data were collected at 10.30 a.m., before switching the cooker ON. The temperature varied from 65 to 97 °C depending upon the sunshine in the morning hours. Energy gain by using cooking water from the water heater is presented in a later section.

5.3. The Cooking Energy Requirements

The setup was tested on a variety of cooking materials starting from water boiling to rice and vegetable cooking. The experimental data were collected from a hotplate, an induction cooker and an electric pressure cooker. A pressure cooker is not usually used for cooking rice or some other food that does not require long boiling times. In Table 4, we present rice cooking energy data using hotplate and induction cooker only. In each experiment, 0.5 kg of rice and 1.0 L of water were added in the pan before putting them on the cooker. Two sets of readings were taken, one with the insulated pan cover and another without it. An experiment was also performed with hotplate and induction cooker directly connected to the grid to compare the performance of the proposed system with the regular cookers.

Table 4. Rice cooking energy data using hotplate and induction cooker; 0.5 kg of rice was cooked by adding 1 L of water.

Cooking Appliance	Insulated Pan Cover	Time of Cooking (min.)	Energy Required (kWh)	Energy from PV, (kWh)
Hotplate	No	36	0.26	0.06
Hotplate	Yes	33	0.24	0.10
Induction cooker	No	28	0.19	0.13
Induction cooker	Yes	26	0.18	0.08
Hotplate (directly connected to the grid)	No	22	0.46	N/A
Induction cooker (directly connected to the grid)	No	14	0.42	N/A

The results show that the induction cooker requires significantly lower energy, which is an expected result as the hotplate body, made from steel frame, conducts and spreads heat to its surfaces and then dissipates it. On the other hand, an induction cooker heats the pan only and the top of the induction cooker is a thick insulating glass that reduces heat loss from the bottom surface of the pan. Moreover, when cooking starts from cool conditions, the hotplate structure is also heated along with the pan, taking a longer time for heating and requiring a higher amount of heat. The insulated pan cover does not have a very strong impact on the energy consumption in either of the cases because rice cooking requires raising the water temperatures close to 100 °C and in the case of slow cooking (here the cooking process is slower than the usual 1200-W hotplate or 1800-W induction cooker), the rice is almost done by the time water reaches the boiling temperature. So, impact of heat retention due to the insulated pan cover is not high as observed in the cooking energy data but was quite significant while we noted the cooling of the cooked rice. The pans without insulated covers cool by 10 °C within 14 min, whereas the same temperature reduction requires close to 25 min when the insulating lid is left on the pans after cooking is complete. For the sake of comparison, we repeated the experiment with a 220-V AC hotplate and the induction cooker. The energy requirement for rice cooking using the hotplate was 0.46 kWh and that while using the induction cooker was 0.42 kWh. When the same food is cooked with higher power, the temperature of the pan and the water inside the pan increases much rapidly, but cooking requires a certain time for the food to soak and soften to our taste. So, the effective loss from the hot pan and the boiling water becomes a major source of energy loss as apparent from the data presented in the Table 4.

To estimate the energy saving in the proposed system when hot water from the water heater is used, we performed another experiment of rice cooking using hot water from the water heater. The experimental results are presented in Table 5. Rice (500 gm) was first washed with water of room temperature and the water was drained. Then, 1 L of water from the water heater was added and the rice was placed on the cooker for cooking.

Table 5. Experimental data of cooking while using hot water (with insulated pan cover).

Cooker Type	Temperature of Room °C	Temperature of Hot Water °C	Temperature of Water Rice Mixture °C	Cooking Time, min	Cooking Energy (kWh)
Hotplate	31	90	63.0	19	0.15
Induction cooker	31	90	62.5	15	0.13

The results presented in Table 5 are interesting in a sense that the energy consumption for the same amount of rice cooking using a conventional electric cooking appliance consumes close to 0.45 kWh (Table 4), whereas with our cooking system, the energy consumption is reduced by a factor of 3. Out of this power consumption, on an average, close to 60% would come from the solar PV. So, actual power consumption from the grid is reduced by a factor of 4.5. However, the energy saving will not be same for all food items, but it is envisioned that the cooking energy requirement from the grid can be reduced by a significant margin. It may be mentioned here that we performed the experiment with and without insulated pan cover and the difference in the energy consumption was very small (less than 0.01 kWh) as the actual loss from the pan was low due to lower cooking time.

To compare the performance of an electric pressure cooker (EPC) with the conventional electric cookers (CEC), a chickpea boiling test was done. Chickpeas were intentionally chosen as they require quite a long cooking time (very similar to beef or some other pulses). An amount of 250 gm of chickpeas was soaked in water for 2 h before cooking. After soaking, the remaining water was drained and then 1.5 L of water was added before energizing the EPC. Out of curiosity, we also performed an experiment with the conventional pressure cooker (CPC) on the hotplate following the same procedure as described. The measured energy requirement data are given in Table 6.

Table 6. Energy data for cooking chickpeas.

Type of Cooker	Insulated Pan Cover	Cooking Time, Minutes	Energy Required, kWh	Energy from PV, kWh
Hot plate	No	110	0.92	0.41
Hot plate	Yes	80 *	0.60	0.22
CPC on hotplate	No	40	0.25	0.17
EPC	-	45	0.21	0.15
Hotplate directly connected to the grid	No	62	1.1	N/A

* The hotplate was switched off after 80 min. The insulated pan cover retained heat and it took another 40 min to complete the cooking.

We performed similar experiments using hot water from the water heater to see how much energy saving is achieved when hot water from the water heater is used. After soaking the chickpeas for 2 h, the excess water was drained and the chickpeas were placed in the pressure cooker. Instead of adding tap water, we added 1.5 L of hot water from the water heater. The hot water temperature was 95 °C and the resultant temperature after adding to the chickpeas were 68 °C and 67 °C in case of conventional pressure cooker (CPC) and the electric pressure cooker (EPC) respectively. The cooking energy data are presented in Table 7.

Table 7. Chickpea cooking using pressure cooker with hot water added from the water heater.

Type of Cooker	Temperature of Hot Water Added, °C	Temperature after Adding Hot Water, °C	Cooking Time, Minutes	Energy Required, kWh	Energy from PV, kWh
CPC	95	68	34	0.21	0.08
EPC	95	67	32	0.14	0.05

The results show significant saving in energy with CPC saving almost 18% and EPC saving close to 30% energy as compared to the data presented in Table 6. The energy consumption data presented in Tables 5–7 show large variations in the percentage of PV energy sharing. This is due to wide variations in the weather conditions (cloudiness) while performing the experiments.

5.4. Cost Comparison

In this section, we make a cost comparison between three different systems—(i) cooking by grid electricity using conventional cooking appliances (ii) cooking by electricity in a solar PV-integrated grid system where the solar PV is connected via a grid-tied inverter and (iii) the proposed system of solar PV integrated to the grid via a DC link. Three different systems have different capital cost as the hardware requirements are different. However, we considered a hotplate as the cooking utensil for all three cases. To compare the cost, the interest rate and depreciation of the hardware are incorporated into the cooking cost of the systems. Here we discuss the systems individually with the parameters used for the calculations. If we consider r as the interest rate, d as the depreciation then annual cooking cost C_C will be

$$C_C = E.C_e + \Sigma C_i \ (r_i + d_i) \quad (3)$$

where, E is the annual cooking energy in kWh consumed from the grid, C_e is the cost of grid energy per unit, C_i, r_i and d_i are the capital cost, interest rate and depreciation, respectively, for the ith capital cost component of the cooking system, value of "i" will depend on the number of capital cost items in a particular cooking system like solar PV panels, inverter, control circuits etc. In all our calculations, the interest rate is assumed to be 8% and the cost of grid electricity is assumed to be USD 0.094/kWh. The monthly cost will be considered as 1/12th of the annual cost. The detailed cost analysis for the individual systems are given below. The cost calculations are based on the energy consumption data we obtained in our experiments. The actual power consumption would vary with the cooking pattern and number of items cooked. We assumed that the cooking energy would be 75 kWh/month for the conventional grid-based system. The estimation has been done by considering 2.5 kWh/day for rice and two side dishes for a family of four persons. This energy consumption figure is within the estimated range suggested by a number of researchers in their publications [17–19]. Tables 4 and 6 show significant energy saving when the proposed system uses a hotplate for cooking. However, in a real-life situation, people may not cook with the full mind set of energy conservation unlike we did during our lab experiments. So, we assume that a minimum of 33% reduction of energy consumption (although Tables 4 and 6 show higher percentage of energy reduction) is achievable even if the cooking is not done very scientifically in a real-life situation. Hence, 50 kWh/month is an equitable estimation in our proposal.

5.4.1. Cooking by Grid Electricity

The basic data for cost calculation are as follows:

- Interest rate—8%.
- Cost of grid electricity—USD 0.094/kWh.
- Energy consumption/month—75 kWh.
- There is no additional capital cost item.

The cooking cost as calculated from Equation (3) is USD 7.05/month.

5.4.2. Cooking by Grid-Tied Inverter-Based System

As our proposed system uses DC, the energy from solar PV is never fed back to the grid and it would be reasonable to compare the system cost of a grid-tied system with our proposed one. For a grid-tied system, solar PV connected to the cooking system via a grid-tied inverter and the energy produced by the PV arrays are directly fed to the grid that reduces the actual energy consumption from the grid. It has the advantage that when the cooking is off, the energy produced by the PV array is still fed to the grid and no energy storage is needed. Our proposed system used a 400-Wp solar PV array and under the average Bangladeshi sunshine condition (4.50 kWh/m^2/day), they would generate an average electricity of 657 kWh/year. Considering the system loss and consumption in the inverter electronic circuit, we expect an average extraction of 85% of solar energy that would give an annual output of 558.5 kWh of electricity to the load.

The relevant data for the cooking system with grid-connected solar PV are given below:

- Cost of grid electricity—USD 0.094/kWh.
- Cooking energy consumed/month—75 kWh.
- Interest rate—8%.
- Capital cost components:
  - A 400-Wp solar PV array with installation—USD 175 (with 5% depreciation).
  - Grid-tied inverter with accessories—USD 150 (with 12% depreciation).
  - Insulated pan cover—USD 2 (with 30% depreciation).

As energy from the PV array is 558.5 kWh/year, the effective energy consumption from the grid is calculated by subtracting the PV energy from the cooking energy ($75 \times 12 - 558.5$) = 341.5 kWh/year that is 38% of a regular grid-connected system. Putting all these data in Equation (3), we determine the cooking cost to be USD 7.13/month.

5.4.3. Cooking by the Proposed System

As already discussed in Section 5.1, on an average 56% of the cooking energy is delivered from solar PV panels. There is at least a further saving of ≈25% energy if preheated cooking water is used from the water heater (Tables 4, 5 and 7). Hence actual energy consumed from the grid, considering PV power and energy reduction due to hot water, will be 16.50 kWh/month (22% of regular grid-connected system). In the proposed system the basic assumptions for cost calculations are given below.

1. Cost of grid electricity—USD 0.094/kWh.
2. Cooking energy consumed/month—50 kWh.
3. Cooking energy consumed from the grid/month—16.50 kWh.
4. Interest rate—8%.
5. Capital cost and depreciation of the utensils/appliances:
   - A 400-Wp solar PV array with installation—USD 175 (with 5% depreciation).
   - Control circuit—USD 55 (with 12% depreciation).
   - Water heater—USD 20 (with 12% depreciation).
   - Insulated pan cover—USD 2 (with 30% depreciation)

Using Equation (3) that incorporates the energy cost and the cost of the capital equipment, the annual cost of cooking is calculated to be USD 4.75/month.

For the sake of easy comparison, the results are summarized in a tabular form as presented in Table 8.

Table 8. A comparative presentation of cooking cost for different electric cooking systems.

System of Cooking	Cost, USD/Month
Grid electricity	7.05
400-Wp solar PV connected to the grid via grid-tied inverter	7.13
400-Wp solar PV connected to the grid via a DC link operating at 130 VDC	4.75

The results show an interesting trend in the cost of cooking. PV-based cooking with a grid-tied inverter is marginally more expensive when only grid power is used. Getting rid of the storage battery and the grid-tied inverters (particularly for small sizes less than 1 kW) reduces the energy cost significantly when compared to the energy cost (~USD 15–25/month) presented in [19,23]. In our proposed system, the cost is lower than the cooking system solely connected to the grid by about 32%. We repeated the calculations for an induction cooker considering the fact that its average price is higher than the hotplate by about USD 15 having a depreciation of 15%. We assume, based on our experimental data in Tables 4 and 5, that an induction cooker will reduce the energy consumption by 10% while being connected to the grid directly. In our proposed system of cooking, the energy saving in an induction cooker is close to 20%. It means the cooking cost using grid electricity only, PV with a grid-tied inverter and the proposed system to be USD 6.63, 6.95 and 4.73, respectively. This is an expected result as the lower energy of the induction cooker offsets the capital cost when connected to the grid. However, in our proposed system the actual consumption of electricity is already quite low and the cost saving in energy does not show any significant gain due to increased capital expenditure.

6. Discussion and Conclusions

This paper presents a number of issues relevant to an efficient clean cooking method. First, it is possible to cook at a much lower power if proper heat insulation is used and the power could be as low as 500 W. Although lower power may increase the cooking time, it is not a dominant challenge as parallel processing of multi-tasking is a common practice in usual kitchens. Cooks usually do preparations for other dishes while one of the dishes is being cooked. In recent years, the price of solar PV modules in the world market has come to a level such that the cost of solar electricity is cheaper than that of the grid electricity in most of the countries. However, integration of the solar PV with the grid is still a challenge as small sized grid-tied inverters are still quite expensive. So, when PV is integrated with the grid for a cooking system, grid-tied inverters make the cooking cost higher than that of the grid electricity. In our proposed system, in spite of the additional cost of the solar PV and other system components, the cost of cooking is lower than the grid-based cooking by about 32% and at the same time, the energy consumption from the grid is reduced by about 78%. However, in a broader case study, these percentages may vary, but an optimally designed PV will deliver a significant share of power to the cooking system and we do not anticipate any large scale deviation from our findings. The results address two very important issues with the grid-connected cooking—first, the power consumption from the grid is so low that the utilities will not feel threatened by over consumption of electricity due to electric cooking, and second, the reduced cost for the consumers makes it economically more attractive.

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