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Full Length Article

Retrofitting domestic appliances for PV powered DC Nano-grid and its impact on net zero energy homes in rural India

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ABSTRACT

There is a growing interest in employing renewable energy conversion systems for supplying power to rural households in India. Such systems have to be designed with maximum efficiency and with minimum intermediate stages. In this context, modifications are proposed for two commonly used rural household appliances; the wet-grinder and the dough-maker for Net zero energy Homes (NZEH). In this paper, AC motors that are conventionally employed for the above two appliances are replaced by Permanent Magnet DC (PMDC) motors, thereby avoiding inverters in the system. The power electronic interfaces for the PMDC motor are also developed. Investigations have been presented to show an increase in energy efficiency and reduction in the cost of the appliances, as a result of this replacement. Roof Top Photo-Voltaic (RTPV) array is the main power source of the proposed NZEH. The new architecture of the NZEH has RTPV and loads directly powered by the PV array, thus creating a DC Nano-grid. The sizes of the PV array required for this NZEH are found to have been reduced with the proposed modifications. Analysis on embodied energy and payback period for the proposed energy system are also presented. This article also presents the energy balance study for a rural home with the new appliances.
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1. Introduction

The increase in need for renewable energy resources and the depletion of fossil fuels have accelerated the development of Net Zero Energy Homes (NZEH). The principle of NZEH is mainly based on balancing annually the energy demand and generation, on a household site. Balancing the demand and generation requires two pronged approach. The first is to work out strategies for building higher energy efficiency appliances for rural households for such NZEH strategies. The second is to promote renewable energy technologies like solar [1,2] wind, biogas and bio-fuel, etc. Policies such as promotion of NZEH will alleviate the challenges faced by the electricity grid because of ever increasing demand.

The back ground for development of DC Nano-grids for rural NZEH is brought out as follows: Earlier, micro-grids of distribution systems were proposed, to augment the renewable sources with the local loads [3–6]. Maintaining the balance of demand and generation in such a micro-gird is challenging, because of the difficulty in keeping the system variables within the limits. Hence, Micro grids are also integrated into the main AC grid [7,8] and the grid acts both as a source and sink of the electric energy, thereby alleviating the problem of intermittency of renewable resources. However, the power requirements of a geographically spread locality have wider variations in power consumption and therefore, to attempt a zero net energy consumption for such a micro-grid requires tedious studies. The control of such a micro-grid also becomes very difficult. On the contrary, installation of DC Nano-grid in every household or consumer site so as to make every home a NZEH is easier and this has been attempted in this paper. A native power network with energy sources, loads and battery storage forms a Nano-grid. Such Nano-grids have the advantage of simple control and the sizing of generators for such a NZEH [9] operation is also simple.

The primary power source in the proposed Nano-grid architecture is a PV array. It is well known that, household rooftop photovoltaic (RTPV) systems have already gained prominence and they have potential profits such as decreasing grid power consumption and increasing power quality [10–14]. However, earlier architectures had RTPVs with inverters feeding the existing AC supply networks and loads. The advantages of DC home appliances and the use of PV energy for such DC loads were not adequately analysed. Further, in spite of the presentation of a DC Nano-grid as a concept

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Nomenclature

C	Capacitor (F)	P_{Inout}	Output power of single phase inverter (W)
Γ	Calculated load	P_{Mout}	Output power of motor (W)
D	Diode	S	Switch
DODE	Daily Depth of Discharge	SPST	Single-pole Single-throw switch
E	Solar irradiation (W/m^2)	V_{DC}	DC voltage (V)
EPT	Energy Payback Time	V_{PV}	PV voltage (V)
I_{DC}	DC current (A)	η_{bat}	Battery efficiency
I_{PV}	PV current (A)	η_{ce}	Converter efficiency
L	Inductor (H)	η_{inv}	Single phase inverter efficiency
LCC	Life Cycle Cost	η_{m}	Motor efficiency
O_{PSH}	Daily average Peak Sun Hour	η_{pv}	PV panel efficiency
P_{Cin}	Input power of converter (W)	η_{total}	Total system efficiency
P_{Cout}	Output power of converter (W)		

in [15–17], the adaptations of home appliances to such a DC Nano-grid are not addressed so far. It is well known that most of the household appliances can be directly driven by a DC supply with proper adaptations. RTPV and battery storage are to be properly sized for such a Nano-grid. The main contribution of this article is the development of the required adaptations for the existing AC driven appliances so as to be fed from a DC supply. Further, the paper presents investigations on the energy pay back, life cycle cost and the confirmation of zero net energy consumption, with such adaptations so as to bring out the benefits of such retrofitting.

One of the design imperatives in the proposed DC Nano-grid for a small rural NZEH is to address the issue of supplying power to appliances which consumes the maximum power. Two such appliances in rural Indian homes are the Wet-grinder and the dough-maker. Hence, adaptations are proposed for these two appliances in this work. Rural households in India have wet-grinders and dough-makers that are normally operated manually or with a single phase AC motor/induction motor/universal motor. It should be noted that when AC motors are employed, an additional DC–AC converter is required in a DC Nano-grid. In this article, the prime mover for the wet-grinder and the dough-maker is a Permanent Magnet DC (PMDC) motor instead of an AC motor. Such a concept removes the necessity for a DC to AC and AC to DC vice-versa conversions, thereby saving energy on the whole. This leads to a decrease in losses on the conversion stage. On the average, this scheme decreases AC to DC conversion losses from about 32% down to 10% [18]. The consequent reduction in energy consumption directly results in reduction of (i) surface area of a solar array, (ii) installation cost and (iii) size of battery storage.

This paper is organized as follows: Section 2 presents the proposed domestic DC Nano-grids in rural India. In Section 3, the development and testing of prototypes of DC powered home appliances and its description, operation and efficiency are presented. Section 4 gives the energy and cost analysis with energy payback time (EPT), life cycle cost (LCC) and power import and export of the DC Nano-grid being examined. Section 5 draws the conclusions of the proposed work.

2. Proposed domestic DC Nano-grids for rural India

Fig. 1 shows the schematic diagram of the proposed DC based Nano-grid system to be installed in every rural household and it consists of (i) solar array as an energy source, (ii) battery storage (iii) DC and AC loads. The normal load demand in the Nano-grid is generally met by the resident/native renewable energy sources. The DC Nano-grid is also integrated to the utility network and hence, PV power output fluctuation is smoothened by the import/-export of power from the grid. The battery storage unit is required in the Nano-grid to guarantee an uninterruptible power supply to the critical loads and to retain power balance in the DC Nano-grid.

In the DC Nano-grid system of Fig. 1, there are three types of power conversion systems to interface the PV source and the household appliances to the DC bus. The first type is the bidirectional DC–DC converter interfaced between the battery bank and the DC bus, to facilitate charging and discharging of the batteries. The second type is the DC–DC power converters employed for regulating the required DC voltage for each appliance. The inverter is the third type of power conversion available for feeding power from the PV array to the rural service connection through a Net meter.

The proposed architecture has four modes of operation as explained below:

Mode I: Solar irradiation and battery power are not available: During this mode, the loads are supplied power from the grid (power import from the grid).

Mode II: Power from PV array is available in excess and battery power is not available: During this mode, the solar power available is more than the load requirement, the surplus power is used to charge the batteries.

Mode III: The solar power is more than the requirement of the load and battery: During this mode, the extra power is sent to the grid (power export to the grid).

Mode IV: PV and grid power is not available and battery power is available: During this mode, the battery will feed the loads. The time period of battery supply is depending upon the size of the load and the capacity of the battery. The operating modes are depicted in Fig. 2. Apart from these modes, when either PV or battery cannot provide full power to the load, power is imported from the grid.

2.1. Peak power tracking

The proposed Nano-grid has two DC–DC converters. The nominal PV array voltage and the battery voltage are chosen to be identical. However, with variation in irradiation and temperature, a maximum power point tracking (MPPT) controller of the DC–DC converter feeding the battery will ensure that the excess energy not utilized by the load is fed to the grid/battery. A charge regulator connected to the battery is designed to ensure charging of battery if the state of charge of the battery falls below the lower threshold. In such case, the excess power instead of being exported to the grid, will be utilized for charging the batteries. The main focus of this paper is retrofitting the home appliances and hence a detailed discussion about the controller is not taken up in this paper.

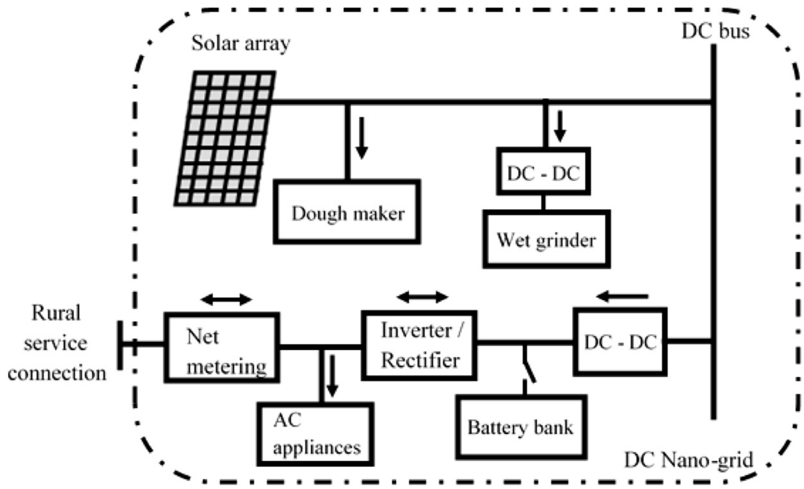

Fig. 1. DC based Nano-grid system.

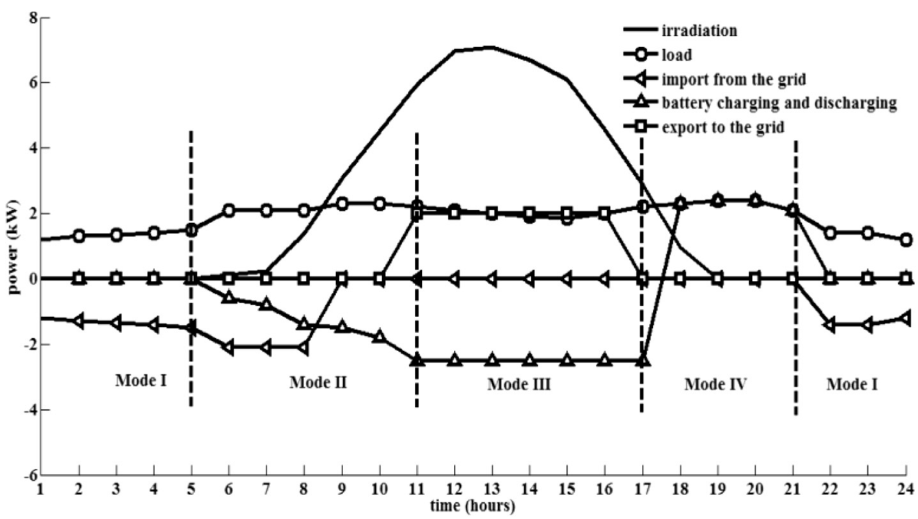

Fig. 2. Operating modes of the proposed domestic DC Nano-grids system.

3. Development and testing of prototypes of DC powered home appliances

Two different laboratory prototypes of PV powered home appliances are developed in this work, for NZEH in rural areas. One is a PV fed wet-grinder and another one is the PV fed dough-maker. These prototypes are explained in the subsequent sections.

3.1. PV fed wet-grinder

3.1.1. Description of the proposed system

A prototype of the solar powered DC–DC drive for a wet-grinder has been developed. The schematic diagram of the PV fed wet-grinder and the photograph of the experimental setup is shown in Figs. 3 and 4 respectively.

It consists of a DC–DC converter and a PMDC motor coupled to a grinder setup. The wet-grinder consists of a stainless steel drum with a small stone and it's driven by an AC motor or a DC motor through a V-belt connection. In the PMDC motor drive, the PV electrical output is either directly coupled or fed through a DC–DC converter. A DC–DC converter will match the PV voltage to the required level.

3.1.2. Operation of the buck-converter

The wet-grinder has a 24 V, 120 W PMDC motor as its prime mover. A MOSFET device is used for ON and OFF switching in the DC–DC buck converter. The pulse width modulation technique is used to control the duty-cycle of the buck converter. These pulses are generated using dsPIC30F4011 microcontroller. The given input voltage from the PV array varies in the range of (30–42) V. Fig. 5 shows the output voltage and current waveform of the experimental setup of a PV fed wet-grinder. The laboratory prototype module of the wet-grinder has been supplied with a voltage of 42 V from a PV array. Two panels are connected in series and two such series connected panels are connected in parallel to form the array.

Table 1 gives the specifications of the components of the wet-grinder used for experimental investigations. The buck converter is fed from the PV array and it maintains a constant output voltage of 24 V using a digital PI controller [19] through a feedback signal. The duty cycle of the buck converter is automatically adjusted for the load and the input voltage variations. The buck converter is operated at 10 kHz and is built with an inductor (L) of 2.72 mH and a capacitor (C) of 562 μF. The variations in solar irradiation causes the PV current to vary accordingly. Consequently, the torque varies with the variation in current thereby resulting in speed

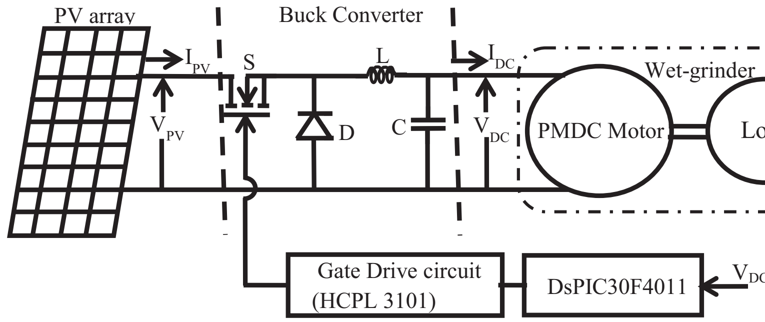

Fig. 3. PV fed wet-grinder with PMDC motor.

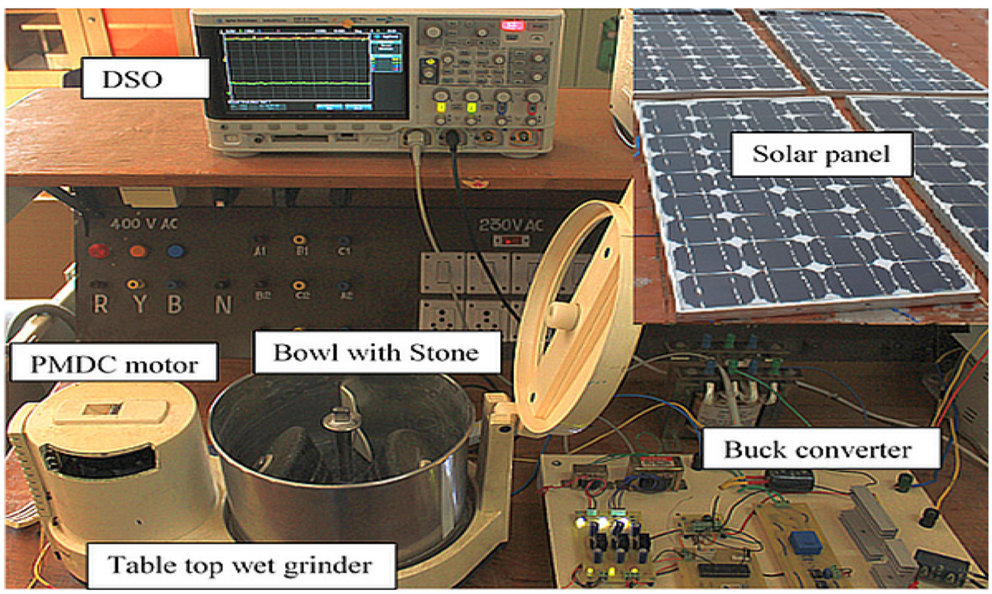

Fig. 4. Experimental setup of PV fed wed grinder.

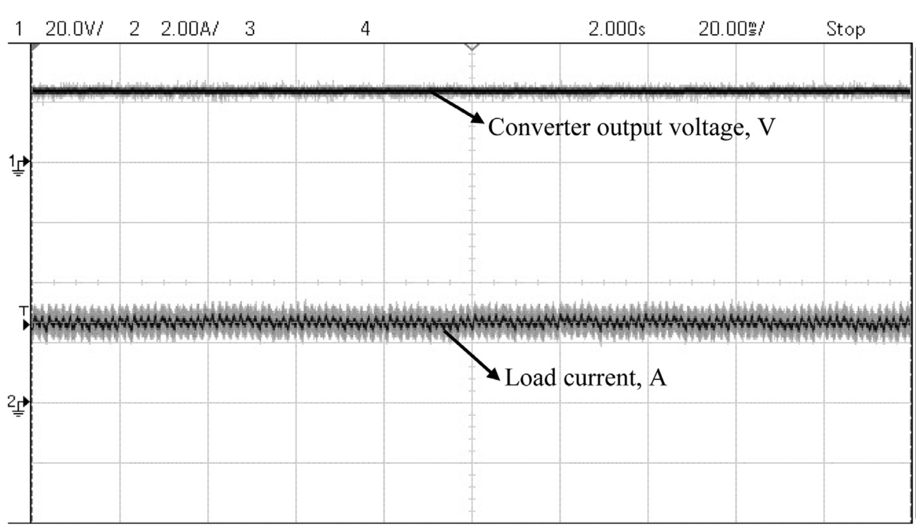

Fig. 5. The output voltage with current waveform of experimental setup of PV fed wet-grinder (20 V/Div, 2 A/Div, 20 ms/Div).

variation also. The efficiency of the PV array varies with solar cell temperature. In practice, it is recommended that PV driven grinding operations are performed in the morning. Variable speed operation do not pose a challenge in the proposed application. Time varying speed of the shaft will only vary the time of completion of the grinding of the wet grains.

The efficiencies of the AC wet-grinder and the proposed DC wet-grinder are compared. A PMDC motor with a rating of 0.5 hp, 24 V,

Table 1
Specification details for PMDC motor, wet-grinder and PV Panel.

Solar PV module	
Type	BP 580
Nominal peak power (P_{max})	80 W
Peak Voltage (V_{max})	17.6 V
Peak Current (I_{max})	4.55 A
Short-circuit current (I_{SC})	4.7 A
Open circuit voltage (V_{OC})	22.10 V
Maximum operating cell Temperature	47 ± 2 °C
Dimensions (L × W × D) mm	1209 × 537 × 50
PMDC motor	
Power	120 W
Armature voltage (V_a)	24 V
Armature current (I_a)	5 A
Speed (N)	3000 rpm
Table top Wet-grinder	
Type	Table top
Capacity	2 L
Stones	2
Plastic material	Food grade material
Drum material	Stainless steel
Dimensions (W × H × D) mm	(272 × 288 × 485)
Weight	14 kg

3000 rpm and an AC motor with 0.5 hp, 220 V, 50 Hz, 3000 rpm are used for comparison. The output voltage of buck converter is applied to PMDC motor-driven wet-grinder system. The proposed DC wet-grinder needs only six PV panels to get the required voltage and current.

The voltages of the commercially available AC motors are rated at 220 V for the same hp. When the same number of PV panels are used with a boost converter for an AC motor, the converter output current falls with an increase in voltage. Hence, the AC motor driven wet-grinder system needs at least 12 panels to get the required voltage and current.

3.1.3. Comparison of wet-grinder efficiency

The efficiency of the wet-grinder unit with a PMDC motor is given as,

$$\eta_{total} = \eta_{pv} * \eta_{ce} * \eta_m \quad (1)$$

where, η_{total} is the total system efficiency, η_{pv} is the PV panel efficiency, η_{ce} is the DC–DC converter efficiency and η_m is the PMDC motor efficiency. Table 2 gives the total system efficiency (η_{total}) with varying PV power (P_{Cin}).

The efficiency of the wet-grinder unit with AC motor is given as

$$\eta_{total} = \eta_{pv} * \eta_{ce} * \eta_{inv} * \eta_m \quad (2)$$

where η_{inv} is the inverter efficiency. Table 3 presents the efficiencies with varying irradiation (P_{Cin}) for an AC motor.

In both cases, the panel efficiency is defined as the maximum power output of a solar PV panel per unit of area. So, the panel average efficiency is nearly 8.2% in Trichy, Tamilnadu. The numerical data obtained for both DC motor and single phase AC motor are simulated at an insolation of 1000 W/m^2. The efficiency of buck converter is ideally more than 90% but the inverter efficiency varies from 39 to 48% with variation in irradiation from 350 to 800 W/m^2. The efficiency of an inverter varies with the load. The variations in inverter efficiency is due to the need for an auxiliary power unit for the control unit of the inverter. It is evident that the efficiency of an inverter is low when feeding light loads, as the power consumed by the control unit of the inverter is significant in these conditions.

In addition, an inverter cannot efficiently feed power to an inductive load such as motors [20,21]. Moreover, in a single phase AC motor driven wet-grinders, the harmonics in the waveforms also reduces its efficiency. The power factor of the AC motor has an additional effect on its the efficiency. It is for these reasons and in addition to these, the requirement of more number of PV panels result is η_{total} of AC motor driven wet-grinder to be very low.

The above factors results in better efficiency of a PMDC motor driven wet-grinder (Table 2) as compared to single phase AC motor driven wet-grinder (Table 3).

3.2. PV fed dough-maker

3.2.1. Description of the PV fed dough-maker

A prototype of the direct driven solar-powered dough-maker has been developed. The schematic of the dough-maker and the photograph of the experimental setup are shown in Figs. 6 and 7 respectively. It consist of PV panels, the PMDC motor and the dough-maker unit. The dough-maker has the blades and the bowl. The PMDC motor is fixed at a small inclination to a stand and its rotating shaft is positioned at the center of the bowl.

The blade is fixed to the rotational shaft. The PV output voltage and current are nonlinear and time-dependent and vary with insolation and cell temperature. When different ingredients like oil, salt and water are mixed through a PMDC motor driven by solar power, the PMDC experiences a variable load over the run-time

Table 2
Performance of PV powered PMDC motor Driven wet-grinder system.

S. No.	P_{Cin} W	P_{Cout} W	η_{ce} %	P_{Mout} W	η_m %	η_{total} %
1	115.2	110.02	95.51	64.03	58.2	4.55
2	143.3	136.79	95.46	85.49	62.5	4.92
3	180.6	168.44	93.27	120.10	71.3	5.46
4	235.9	217.87	92.36	161.66	74.2	5.82
5	294.4	271.20	92.12	212.89	78.5	6.29
6	372.1	342.29	91.99	283.07	82.7	6.80

Table 3
Performance of PV powered AC motor driven wet-grinder system.

S. No.	P_{Cin} W	P_{Cout} W	η_{ce} %	P_{Inout} W	η_{inv} %	P_{Mout} W	η_m %	η_{total} %
1	315.38	303.49	96.23	119.05	39.23	57.26	48.1	1.48
2	399.68	382.97	95.82	165.13	43.12	89.00	53.9	1.83
3	516.36	494.36	95.74	220.43	44.59	128.29	58.2	2.04
4	649.62	620.51	95.52	279.29	45.01	175.11	62.7	2.29
5	733.09	698.12	95.23	322.88	46.25	227.30	70.4	2.69
6	816.9	774.25	94.78	372.88	48.16	272.95	73.2	2.99

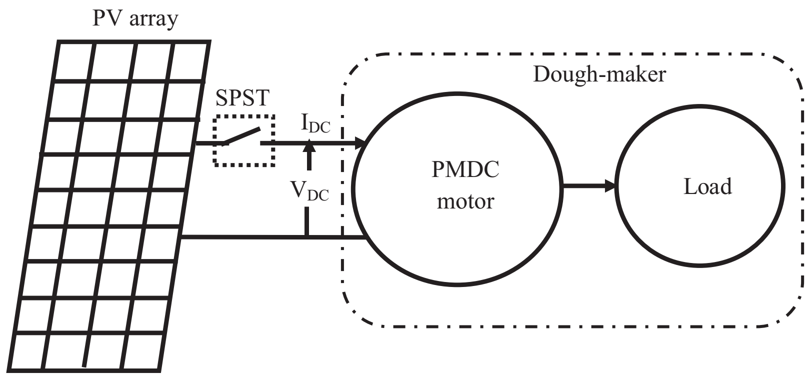

Fig. 6. PV dough-maker with direct coupling.

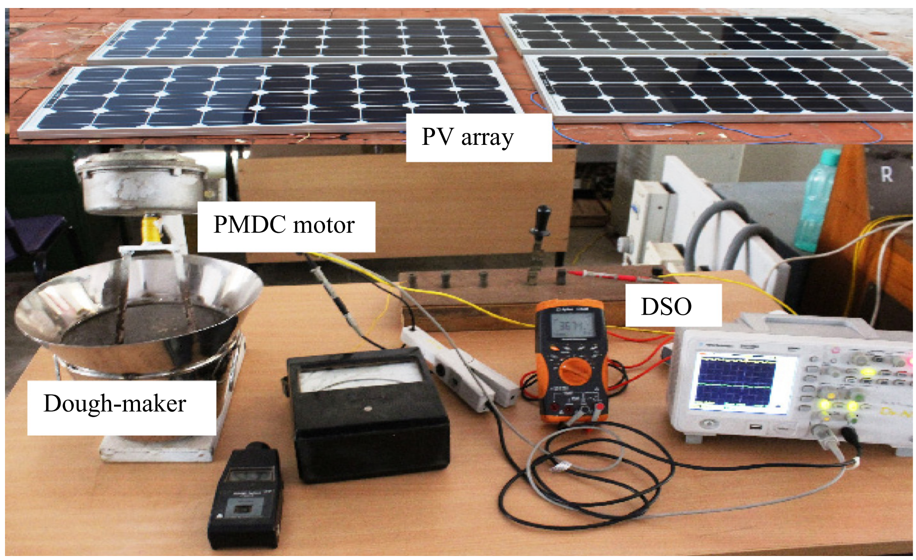

Fig. 7. Experimental setup of PV fed dough-maker.

Table 4
Specification Details of PMDC motor and Dough-maker.

Dough-maker	
Type	Stand Mixer
Capacity	250 g flour
Container material	Stainless steel
PMDC motor	
Power	150 W
Rated voltage	36 V
Rated current	4.2 A
Rated speed	260 rpm

period, due to the variation in the consistency of the dough. The details of the PMDC motor and dough-maker are listed in the Table 4.

3.2.2. Steady–State operation of the PV fed dough-maker

As PV array is connected to the PMDC motor, the operating point of the PV array depends on insolation and load. The photocurrent and short-circuit current are linear functions of PV insolation and the open-circuit voltage is a logarithmic function of the PV insolation. PV short-circuit current is more sensitive than open circuit voltage for changes in insolation. The PV array open-circuit voltage decreases with the increase in cell temperature [22].

Whenever the PV cell temperature increases, the reverse saturation current of the PV array increases suddenly, which leads to a drop in the open circuit voltage. However, there is only a very small increment in short-circuit current with the increase in PV cell temperature. Hence, in direct driven operation, the dough making process in the NZEH needs to be carried out during noon time or immediately after noon. The maximum starting current of the PMDC motor is dependent on the armature resistance and the short-circuit current of the solar PV array. Fig. 8 shows the voltage and current waveform of the experimental setup of dough-maker fed directly by the PV array (Time–2:20 pm, irradiation–374 W/m^2, load–150 g, voltage–36.74 V, current–3.419 A).

3.2.3. Dough-maker efficiency

The motor runs at low speed at low irradiation conditions and when the solar irradiation increases the motor speed also increases. Hence, the motor efficiency is low at poor solar irradiation. The numerical data of PV powered PMDC motor driven dough-maker system is shown in Table 5. It is found that the dough-maker driven directly by a PV array has higher efficiency than AC motor driven unit because of the same explanation given for wet-grinders i.e. the absence of the inverter.

4. Energy and cost analysis

The design of the PV system is based on the energy balance between the existing solar energy on the region and the daily

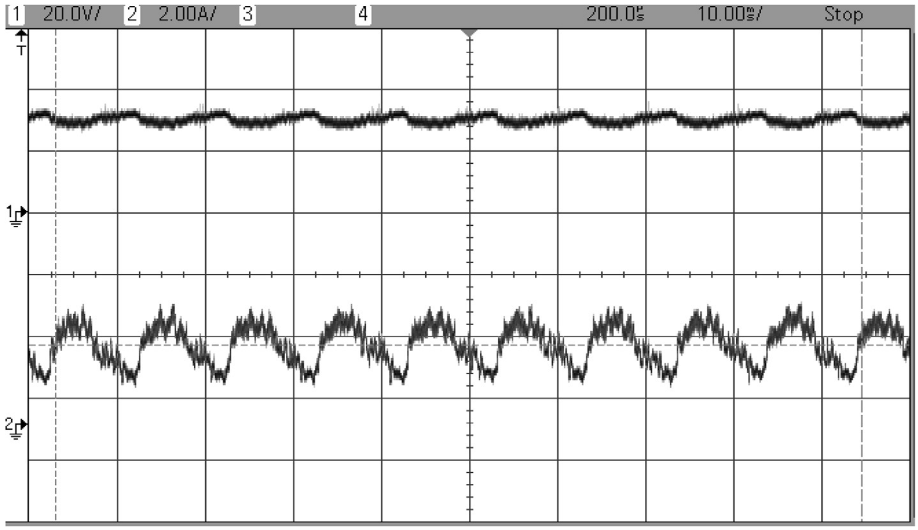

Fig. 8. The output voltage with current waveform of experimental setup of PV directly coupled with dough-maker (20 V/div, 2 A/div, 10 ms/div).

Table 5
Performance of PV powered PMDC motor driven dough-maker.

S. No.	P_{in} W	P_{Mout} W	η_m %	η_{total} %
1	96.28	54.12	56.22	4.61
2	105.2	64.32	61.15	5.04
3	118.01	80.74	68.42	5.62
4	133.49	94.79	71.01	6.03
5	142.5	104.90	73.62	6.40
6	182.3	136.85	75.07	6.71

amount of energy required by the load [23]. Generally, energy consumption of the load is calculated in kWh. The number of PV modules required is calculated after the net load is ascertained.

Initially, the total power required to be generated from the PV panels is obtained from (3),

$$\text{Total PV panel watts (W)} = \frac{\Gamma\,\text{Wh}}{O_{PSH} * \eta_{total}} \tag{3}$$

Where, Γ Wh is the calculated load and, O_{PSH} is the daily average peak sun hour.

The required battery capacity is calculated from the days of autonomy and the load in Watt hours.

The battery in Watt hours is obtained by,

$$\text{Battery Wh} = \frac{\text{Source Wh}}{\text{DODC} * \eta_{total}} \tag{4}$$

Where, Source Wh is the product of load and battery autonomy.

And, battery Ah is obtained from,

$$\text{Battery Ah} = \frac{\text{Battery Wh}}{\text{Voltage (V)}} \tag{5}$$

It should be noted that since η_{total} for a system with DC appliances is much higher than η_{total} of system with AC appliances (because of the addition of inverters in the system), the PV panels required for the proposed system is less than that of conventional AC systems. The load taken for PV panel sizing is 3087 Wh per day, based on cumulative load evaluation. A load correction factor of 90% is taken since batteries and other components of the system are not 100% efficient. The various appliances and their consumption are given in the Table 6. It is found the Table 6 that the wet-grinder and dough-maker consumes about 3% of the total consumption of energy. However, the power rating of the wet-grinder and dough-maker are quite high compared to other appliances. It is for this reason, power electronic interface and appropriate drive for the two appliances have been investigated. PV sizing to source these two high power appliances will therefore supply the required demand of all other household appliances. Further, the period of usage of these high power appliances is quite low compared to other appliances.

In order to decide the size of the PV array, the efficiency of the DC–DC converter efficiency is taken as 90%, motor efficiency as 70%, battery efficiency as 85% and daily depth of discharge as 60%. According to Energy Authority of India (EAI) report, the peak sun hours is 5.13 for Tiruchirappalli.

The required power rating of PV array for the DC Nano-grid is found to be 1157 W using (1). Based on (3), if PV modules of 80 W peak power are employed, fourteen such PV modules are

Table 6
Household Load Evaluation.

S. No.	Appliances	Watts	Quantity	Hours/day	Average Wh/day
1	CFL	28	3	6	504
2	Wet-grinder	120	1	0.3	36
3	Dough-maker	150	1	0.3	45
4	Fan	28	2	4	224
5	TV (19″ color)	70	1	3	210
6	Water pump	60	1	2	120
7	Refrigerator	100	1	15	1500
8	Laptop	35	1	4	140
Total					2779

CFL: Compact florescent Lamp, TV: Televisions.

Table 7
Embodied Energy of components of PV system.

Components	Embodied energy (kWh/m^2)
Silicon manufacturing (E_{mfg})	782.64
Installation (E_{inst})	150.6
Transport PV from factory to installation site (E_{trans})	42.8
Balance of system (E_{bos})	398
Decommissioning and Disposal (E_{disp})	0

required. These 14 PV panels are connected as a string combination of parallel and series connections. The required capacity of the battery storage is measured using (4) and (5) (i.e. number of hours the battery should supply the load).

The total capacity of the storage battery is found to be 24 V, 280 Ah for 1 day autonomy for the load taken. The energy payback time (EPT) and life cycle cost (LCC) is analysed for a single household. The net zero energy home operation is also analysed for a single household.

4.1. Energy payback time

To estimate the EPT of a PV system for the DC Nano-grid, the annual energy output and the energy required for manufacturing of PV cell/module, operation and maintenance, installation, transportation and disposal/salvage is considered.

$$EPT = \frac{\text{Embodied energy } (kWh/m^2)}{\text{Annual energy output } (kWh/m^2/year)} \tag{6}$$

$$\text{Embodied Energy} = E_{mfg} + E_{inst} + E_{trans} + E_{bos} + E_{dis} \tag{7}$$

The embodied energy is a summation of manufacturing energy (E_{mfg}) including operation and maintenance energy, installation energy (E_{inst}), transportation energy (E_{trans}), disposal energy (E_{dis}) and balance of system energy (E_{bos}). Balance of system includes electrical components like DC–DC converter, inverter and some mechanical components.

The embodied energy values are tabulated in Table 7 based on [24–28]. The surface area of 14 panels used for the experimental investigation is 9.24 m^2. The embodied energy is 1374 kWh/m^2, so the total embodied energy for 14 Panels is evaluated using (7) as 12,696.12 kWh. And the annual energy output is calculated based on average solar irradiation, efficiency of solar cell, packing factor and efficiency of balance of system in Tiruchirappalli.

The variation of average energy of 14 panels for a period of one year along with irradiation is shown in Fig. 9. The annual average energy production of 14 panels is 1594.32 kWh/year. So the EPT of 14 panels is calculated using (6) and the values are shown in Table 8. The EPT for 14 panels is around 7.963 years.

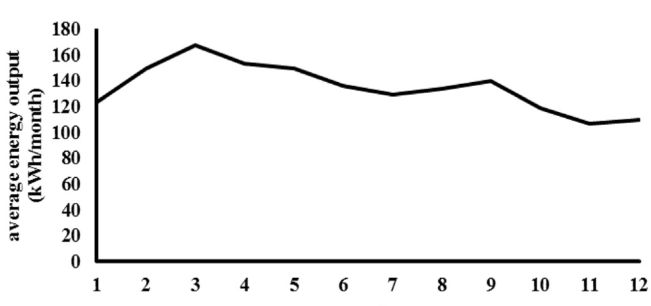

Fig. 9. Monthly average energy.

Table 8
Energy Payback Time.

No. of PV panel	Embodied Energy (kWh)	Annual energy output (kWh/year)	EPT (in Years)
14	12696.12	1594.32	7.963

Table 9
Data for cost analysis of solar home appliance system.

Description	Value
PV system lifetime	25 years
Initial cost of 80 W PV module	$80
PV installation cost	10% of initial PV cost
O&M cost of PV system per year	2% of initial PV cost
Discount rate	6%
Cost of battery (including battery charge controller)	$1420

3.2. Life cycle cost

Most of the available literature have analysed LCC as the major criteria for cost analysis of solar energy systems. The total LCC depends on the sum of all the present worth of the PV module, converter and cost of the installation, operating and maintenance cost and replacement cost. The details of the cost of all the components are shown in Table 9 [28–31]. The initial investment cost (C_{IN}) of 14 panels is $1120; the installation cost (C_{INST}) has been assumed 10% of total initial investment cost of the PV system and is taken as $112. The repair and maintenance cost ($C_{R\&M}$) has been assumed 2% of total initial investment cost and discount rate is 6% from this repair and the maintenance cost is $267.38.

Thus, the overall LCC [24–28] of the solar home appliance system is given by,

$$LCC = C_{IN} + C_{CONV} + C_{INST} + C_{R\&M} + C_{BAT} \tag{8}$$

C_{IN} = Initial investment cost of PV module, C_{CONV} = Initial investment cost of the converter, $C_{R\&M}$ = Repair and Maintenance cost, C_{INST} = Installation cost, C_{BAT} = Battery with charge controller cost.

The total LCC cost for the proposed DC Nano-grid, as obtained from (8) is $2945.38.

4.2. Power export/import study

The yearly energy requirement of a normal household is observed for a year. The annual energy difference as currently monitored between energy generation and consumption (electricity) is approximately −0.227 MWh/year.

Fig. 10 shows the yearly PV generation as compared to the electrical demand. These two are accumulated on a monthly base.

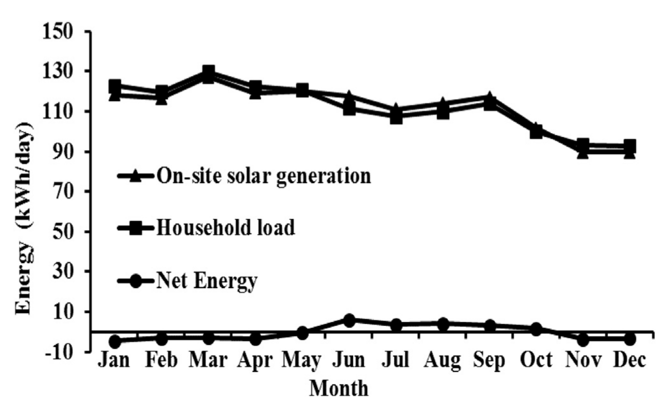

Fig. 10. Electricity consumption and generation in the Household.

Table 10
Outcomes of the final Energy balance.

Electricity (MW h/year)	
Generation	1.594
Load	1.367
Imported from the grid	0.186
Exported to the grid	0.318
Load-generation balance	−0.227
Import–export balance	−0.227

Table 10 shows the final annual energy balance of a household with DC Nano-grid. Both imported-exported energy and generation-load balances are shown in Fig. 10. There is a surplus of energy (0.227 MWh) from the Nano-grid which is fed to the main grid. These results confirm that the household can be considered as a NZEH, when the encountered energy flows are calculated over a period of a year.

5. Conclusions and scope for future work

This study has developed a frame work for solar Net Zero Energy Home (NZEH) systems for a single family household in rural India with retrofitting of two appliances with PMDC motors. Remote villages in Tiruchirappalli district of India are considered for this case-study. Wet-grinder and dough-maker are the two top power consuming appliances in a rural household and require more number of PV panels for sourcing them. The proposed modifications in the two rural domestic appliances, results in employing fewer PV panels for the DC Nano-grid as compared to the existing AC systems, thereby guaranteeing cost effectiveness for NZEH implementation. The power electronic interface for the adapted appliances is also simple. Energy efficiency and simplicity are ensured respectively by the minimum number of conversion stages and ease of control. The modest energy payback time (EPT) for NZEH ascertains the feasibility of the proposal. Life cycle cost (LCC) and NZEH calculations also endorse the usefulness of the proposed retrofitting.

PV systems are connected at the consumer sites in the proposed architecture. So, the peak load on a distribution transformer in the household area will be brought down. In addition, the burden on residential distribution circuits is also reduced. (e.g., distribution transformer and cables) thereby decreasing the events of line overloads, premature transformer failures and its associated outages. Further, the voltage profile of the distribution network will also be improved. The total system losses will also drop when the proposed DC Nano-grids are installed. The above tangible benefits can be ascertained by additional investigations in a future work.

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