Off-grid electrification with solar home systems: An appraisal of the quality of components

Shahriar Ahmed Chowdhury[1]**, Monjur Mourshed**[2,*]

[1]Centre for Energy Research, United International University, Dhanmondi, Dhaka, Bangladesh

[2]School of Engineering, Cardiff University, Cardiff, CF24 3AA, United Kingdom

Abstract

Solar home systems (SHS) are seen as an attractive option for off-grid electrification in rural areas in developing countries. The combined effect of declining photovoltaic module costs and success in micro-finance has resulted in increased SHS installations in emerging economies in Asia such as Bangladesh. Majority of the SHS components are now manufactured locally with the exception of PV cells. Considering the role of component quality in SHS performance, technical quality of four key SHS components: solar panel, battery, charge controller and lamp circuit (inverter) from market-leading manufacturers were evaluated in this study in laboratory settings, against national and international standards. All of the tested components met some evaluation criteria in their respective categories but none met all. Key performance failures were found to be related to inverter efficiency, reverse polarity protection in charge controllers and battery capacity, which are critical for optimum performance of the system. Findings in this study point towards an ineffective regulatory mechanism for quality assurance and the protection of consumer rights, which needs to be rectified for maintaining public confidence and sustaining the growth of SHS based off-grid electrification.

Keywords: Solar home system (SHS); Component quality; Solar photovoltaic (PV) panel; Battery; Charge controller; Bangladesh

---

*Corresponding author
Tel: +44 (0)29 2087484
Fax: +44 (0)29 2087 4716
Email: MourshedM@Cardiff.ac.uk
Web: http://www.engin.cf.ac.uk/
Corresponding author

1 Introduction

1.1 Energy infrastructure development challenges

Access to modern energy services is essential for economic development and human wellbeing; and yet 1.2 billion people or 17% of global population lack access to electricity, more than 95% of whom are in countries in sub-Saharan Africa and developing Asia[1]. One of the key challenges faced by most, if not all developing countries, is the sustainable development of energy infrastructure to provide the population with access to convenient forms of energy at an affordable price, against a backdrop of growing demand [1]. The increasing demand for electricity is a particular challenge for both developed and developing countries and will require the installation in the coming decades of as much power generation capacity as was installed in the entire 20th century [2]. Much of the growth in demand for electricity is coming from non-OECD (Organization for Economic Cooperation and Development) nations [3]. Countries with high economic growth and significant population such as China and India are leading the trend in electricity demand growth. Although the development and expansion of electricity generation in most energy intensive countries were predominantly based on fossil fuel [4], the importance of increasing the share of renewable energy in the generation mix to reduce greenhouse gas emissions and to enhance energy security is well recognized [5, 6].

Bangladesh demonstrates a number of energy infrastructure development challenges faced by developing countries with relatively higher rates of economic growth, growing demand for electricity and lower rates of access to electricity [1]. The country experienced steady economic growth during the past decades and since 2004 annual growth in gross domestic product (GDP) has been around 6% [7], against an electrification coverage of 62%[2] and one of the lowest per capita electricity use of 290 kWh [8]. The average rate of annual growth in demand for electricity was 7.16% for the period 2001–2011. Increases in energy intensive industries and rising energy use from urban buildings are two of the primary reasons for the burgeoning growth in demand for electricity. A relatively high population growth [9], rapid urbanization [10], the lack of suitable land for buildings and increasing urban temperatures due to urban heat island and global climate change [11] are suggested to contribute further to the growing demand. In contrast, annual growth in electricity generation capacity was variable with a range of -1.69–25.95%[3] between 2001 and 2011. Demand always outstripped supply [8], resulting in rolling blackouts throughout the year, albeit with varying intensities due to variations in seasonal demand. Chronic power outages, coupled with low levels of electrification had a severe

[1] Around 80% of the population without electricity live in rural areas in developing countries. The statistic is obtained from the International Energy Agency (IEA). http://www.iea.org/topics/energypoverty

[2] Electricity access is disproportionately distributed in Bangladesh. The share of access is 90% in urban areas compared to 48% in rural areas in 2013. Source: IEA World Energy Outlook 2015. http://www.worldenergyoutlook.org

[3] The highest annual growth in generation of 25.95% occurred in 2011 and the lowest of -1.69% was in 2007.

impact on the economic performance of the country [12] and growth [13], with a significant knock-on effects on quality of life and society.

1.2 Access to electricity and policy directions

Apart from the impacts on industry and economy as a whole, the lack of adequate supply affects the population disproportionately. Rural areas suffer from blackouts and brownouts more often than urban areas where economic activities are concentrated[4]. On the other hand, expansion of the electricity grid is frozen or kept to a minimum in rural areas until a reasonable level of parity is achieved between the growing demand and generation in the existing grid-connected areas. Evidence of the slow progress in increasing access can be found in the recently published (2010) power sector master plan (PSMP) of Bangladesh, which appears to be biased towards increasing generation capacity [15]. The 2010 PSMP illustrates long-term policies until 2030 and focuses on the development of offshore facilities for importing coal and liquefied natural gas (LNG) to create a resilient supply chain in the context of dwindling local gas reserve. Planned increases in the generation capacity are based on the proposed extension of coal and LNG supply chains. There are plans to import hydroelectricity from neighboring countries such as Nepal and Bhutan via India and to construct a cross-border grid for the import of electricity. However, the 2010 PSMP does not discuss in detail how access to electricity will be improved, in particular in rural areas, other than suggesting the development of domestic wind and solar-based generation.

1.3 Solar off-grid electrification in Bangladesh

Solar and wind are the two key renewable energy technologies highlighted in the PSMP and other energy sector policies in Bangladesh [15, 16]. However, the potential for off-grid wind is low, except in coastal areas [17]. Solar, mostly photovoltaic, appears to be the preferred policy direction for off-grid electrification. Solar PV is particularly suitable for areas with low consumer density, where grid connection may not be economically feasible in the short term [18]. A standalone solar home system (SHS) with battery for energy storage is widely accepted as a mature and effective means for off-grid electrification where demand for electricity is relatively low [19, 20], typically less than 100 W. Large-scale implementations of SHS was initiated by the Infrastructure Development Company Limited (IDCOL), a wholly owned subsidiary of the Government of Bangladesh (GoB) [21]. Funds for the project came from GoB, as well as from donor agencies such as International Development Association (IDA), Global Environment Facility (GEF), Asian Development Bank (ADB), Islamic

[4] An evaluation of daily generation, demand and load shedding in Bangladesh suggests that on a typical day the intensity of blackout in regional cities and rural areas is more than the intensity in the capital, Dhaka. The intensity refers to the percentage of load shed as well as the duration of load shedding (blackout). In some cases, the percentage of load shed outside Dhaka is twice the percentage in the capital. Daily demand, generation and shortfall data can be found on the website of Power Grid Company of Bangladesh (PGCB), the organization responsible for the maintenance and upgrade of the electricity grid in Bangladesh [14].

Development Bank (IDB), Gesellschaft für Internationale Zusammenar-beit (GIZ) and Kreditanstalt für Wiederaufbau (KfW) [22]. The program is implemented through 47 partner organizations (PO), mostly non-governmental organizations (NGO), who receive grants and concessionary loans from IDCOL upon installation of SHSs in rural households. Over the lifetime of the project, only 17% of the project cost has been disbursed as grants while the rest (83%) has been provided as loan, indicating the long-term financial viability of the project [22].

Partner organizations are primarily responsible for the design, installation and after-sales service of the SHS and operate under approved guidelines from IDCOL. Most of these POs have extensive national microcredit networks and have the necessary infrastructure to provide service to the majority of the rural population. An enduser's purchase of an SHS is administered by the PO's microcredit financing system. The majority of the system components are sourced from local IDCOL-approved suppliers and original equipment manufacturers (OEM). The segregation of administration, manufacturing and sales of SHS in Bangladesh has encouraged the development of a local supply chain [19], creating up- and down-stream jobs in all stages of the system lifecycle. The market has grown steadily over the past decade and as of December 2015, over 3.90 million SHSs have been installed in off-grid areas of Bangladesh [22]. Year-wise installations of SHS in Bangladesh for the period 1997–2015 are given in Figure 1, showing exponential growths in annual and cumulative installations.

<Figure 1 is about here>

1.4 Solar home system and components

SHSs discussed here are standalone solar power systems to provide electrical energy to households in off-grid rural areas. An SHS comprises a solar panel to convert sunlight into useful electrical energy, a battery as the energy storage medium to meet demand during low/zero solar resource availability, a charge controller to regulate the charging and discharging of the battery, and some loads. Connected loads are predominantly lighting loads; the typical is an 8 W fluorescent[5] lamp. To enable deep discharge, industrial-grade flooded-cell batteries are predominantly used in Bangladeshi SHSs, as opposed to automotive-grade batteries. A typical solar home system is illustrated in Figure 2.

<Figure 2 is about here>

IDCOL supported SHS installations are carried out by the listed POs, who procure the systems and components from IDCOL-approved component manufacturers and suppliers. The process of granting rights to supply approved components is as follows. A supplier intending to market a specific component first seeks compliance with IDCOL's specification from an IDCOL-recognized testing

[5] There are indications of steady penetration of light emitting diode (LED) lamps, some of which are locally produced. However, the widespread diffusion of LED remains to be seen.

authority such as an adequately equipped laboratory at a higher education institution. IDCOL then grants the supplier the right to supply the certified component to the POs under the terms of reference of the umbrella SHS initiative. The compliance testing is conducted according to the specifications [23], developed by the technical standards committee (TSC) of IDCOL. The compliance requirements in the specifications have two levels: mandatory and recommended. Some elements of compliance, critical for the performance of an SHS, are classed as 'recommended' which are open to interpretation and possible manipulation by manufacturers.

A field appraisal of solar home systems in Bangladesh was carried out by Chowdhury et al. [19] involving sixty installations in various locations in the country. Findings from their field investigation suggested, among other things, that there were significant variations in the performance of the systems due to varying qualities of system components. One of their conclusions and suggestions for future research was to carry out detailed performance assessments of system components in a laboratory setting. The sheer size and growth[6] of the Bangladeshi SHS market make it imperative to carry out these assessments to identify issues related to quality control and assurance, if any, and update specifications and quality assurance mechanisms to ensure long-term sustainability of the initiative.

1.5 Aim and outline

The research discussed in this article is aimed at assessing the performance of SHS components, namely solar panel, battery, charge controller and inverter, against local (e.g., IDCOL specifications [23]) and international specifications, standards and guidelines.

The rest of the article is as follows. The methodology adopted for the selection of sample components and testing procedures are described next. Testing criteria, obtained from local and international specifications and guidelines are elaborated, justified and contextualized. Results from the testing are deliberated, and implications on the performance of SHSs are discussed, followed by concluding remarks.

2 Methodology

The key objective of this research and of the laboratory investigations is to assess component quality, predominantly against the binding national technical specifications from IDCOL [23], which provides a technical framework for installation and after sales service by partner organizations and vendors within the umbrella SHS project. However, it was observed during the initial stages of the research that the IDCOL criteria alone were not sufficient to adequately ascertain the performance of the

[6] There are 3.9 million installed SHSs in Bangladesh as of December 2015. The number is expected to rise to 4 million in total by 2016 [22]. These numbers are for the IDCOL-supported installations only and accounted for up to 86% of total installations in the country in 2009 [24].

components. This is because of the lack of sufficient details on either the criteria or the testing procedure. IDCOL criteria were, therefore, augmented with international standards and guidelines to obtain a comprehensive picture. The following international standards and specifications were consulted to identify the criteria for performance assessment.

- IEC 62509:2010 – Battery charge controllers for photovoltaic systems – Performance and functioning [25].
- IEC 60896–21:2004 – Stationary lead-acid batteries – Part 21: Valve regulated types – Methods of test [26].
- IEC 61215:2005 – Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval [27].
- Universal technical standard for solar home systems, developed by the Directorate General for Energy (DGXVII) of the European Commission [28].
- Solar home system implementation standard in China by the National Development and Reform Commission [29].
- Photovoltaic quality assurance for solar home system in Nepal by the Nepalese Ministry of Environment, Science and Technology [30].
- Specifications for solar home systems and service standards in Sri Lanka by the Renewable Energy for Rural Economic Development Project [31].

The specifications for individual components that were analyzed and tested are given in Table 1, along with the required level of compliance needed for IDCOL approved status. Sample collections are discussed next, followed by the testing procedures for batteries, charge controllers and inverters.

2.1 Collection of test samples

SHS components were collected at random for laboratory tests, from the production line or storage of the original equipment manufacturer (OEM) when they were ready for shipping, except for PV panels which were collected randomly from the POs warehouse. Batteries were collected directly from the production line to reduce the possibility of bias due to the loss of capacity of batteries during storage. Manufacturers were chosen based on their market share and only the significant ones were selected. Components were collected for testing from four battery, six charge controller, five inverter and 21 PV panel manufacturers. Manufacturer names were letter-coded to maintain anonymity. Four battery manufacturers were coded as A, B, C and D, whereas charge controller manufacturers were coded as G, H, I, J, K and L. Inverter (fluorescent lamp circuit) manufacturers were coded as P, Q, R, S and T. 21 panel manufacturers were coded as M1, M2, ... M21.

<Table 1 is about here>

There are 890 approved models of PV panel from different manufacturers in Bangladesh. During the collection for testing, only 66 different models from 21 manufacturers were found to be in stock at various partner organizations (PO), even though each supplier typically has more than one approved model. Attempt was made to collect at least two samples for each model, except for nine for which only one panel each was available for testing – making the total count of panels tested to 123. Various statistics of the tested panels are given in Table 2. Of the tested panels, 109 were international and imported, while fourteen were locally assembled. Rated capacities of panels ranged from 10 to 100 Wp. 20 Wp panels were the most prevalent (n = 22), closely followed by 40 Wp (n = 20) and 50 Wp (n = 19). This represents the situation in Bangladesh where majority of SHS installations are small (<50 Wp).

<Table 2 is about here>

There are fourteen IDCOL approved battery manufacturers in Bangladesh. Among them, four local manufacturers supply the majority of the batteries. Thirteen samples of different capacities from the four major manufacturers were tested in this research, ranging from 55 Ah to 130 Ah, details of which are given in Table 3. The most common charge controller used for SHS installations has a rated voltage of 12 V and current of 10 A, same as the tested charge controllers. 24 charge controllers from six different manufacturers were tested in this research. The tested fluorescent lamp circuits or inverters are capable of high frequency (>20 kHz) outputs with a power rating of 6–8 W. These are used to run fluorescent lamps of 10 W (T8) from an inverter output of 6–8 W. This was found to be a common practice among POs, mainly to consume less power from the battery but at the expense of lighting quality and longevity. Ten inverters from five leading manufacturers were tested in this research.

<Table 3 is about here>

2.2 Tests on PV panels

The PV panel is the most important part of an SHS, the quality of which needs to be strictly monitored due to their impact on system design and operational performance. PV panels also enjoy the highest longevity of the SHS components and are expensive to replace later. Because of the lack of an accredited laboratory for testing of PV panels in Bangladesh, the testing facilities of three PV panel assembling plants were used for this research. DC power output of panels were measured under standard test conditions (STC); i.e., incident radiation of 1000 W/m^2, a cell temperature of 25°C and an air mass of 1.5 (AM 1.5 spectra), as specified in the International Electrotechnical Commission (IEC) standard 60904-3 [32]. Panels were tested in the panel assembling plants. The panels that show capacity less than the rated were double checked by testing that panel in another assembling plant. The sun simulator was calibrated using a standard panel before testing.

2.3 Tests on batteries

The battery is the most vulnerable part of an SHS and often considered as the weak point of a photovoltaic system in terms of cost, lifetime and reliability [33]. Among all components of an SHS, the battery observes the extremely variable lengths of service life, which is dependent on its quality and usage. Both overcharge and deep discharge are harmful for batteries. If a battery is allowed to operate for long in the deep discharge condition, the battery plate suffers from sulfation, which refers to the practically irreversible formation of highly crystalline lead sulfate on battery plates. Sulfation prevents the electrodes to revert back to an electrochemically active form and results in a rapid loss of capacity [34], which is the dominant factor for the ageing of a battery [35]. Although sulfation can be removed by boost charging [36–38], it often causes permanent damage to the battery. On the other hand, overcharging causes water decomposition and results in grid corrosion [34]. Keeping sufficient margin for cut-off voltages will result in the under-utilization of the harnessed solar energy and battery capacity. It is, therefore, important to optimize the selection of the battery, its specifications and management mode [39] for smooth operation of an SHS.

Batteries tested here are 12 V rechargeable deep-cycle flooded lead acid (lead antimony grid) batteries with tubular positive plate. All batteries are supplied to the market with a warranty of five years, corresponding to its cycle life, before its residual life drops below 80% of the rated capacity. IDCOL specifications goes further and suggests that it must exceed 1500 cycles at 25°C when discharged down to an average depth of discharge (DOD) of 75 % at the discharge rate of once every ten hours [23]. Tests performed on batteries are described below.

2.3.1 Battery capacity

The capacity was determined with constant current (C/10) and according to the method proposed by the IEC in the standard 60896–21 [26]. Constant current discharging was continued up to the discharged voltage at 10.5 V (cell voltage of 1.75 V). This was conducted by connecting a resistive load (rheostat) to the battery terminal along with an ammeter. The ambient temperature is kept constant at 25°C during the discharging cycle. Temperature correction in capacity calculation was not considered. Four cycles of charging and discharging were conducted and the average of the last three cycles were taken to calculate the capacity of the battery.

2.3.2 Specific gravity of the electrolyte

The specific gravity of the electrolyte of fully charged and discharged batteries were measured by a calibrated hydrometer. Four charging and discharging cycles were performed. Specific gravity measurements of the electrolyte of six cells were taken immediately after every charging and discharging cycles. The average of the specific gravities of six cells were taken as the specific gravity of the batteries. The reading of the first cycle was not considered. The average of the last three cycles were taken as the specific gravity of the battery at charged or discharged condition.

2.3.3 Depth of Discharge at low voltage disconnect

For this test, the discharge time and voltage were recorded for four discharge cycles. The batteries were discharged at a constant current rate (C/10) up to the low voltage disconnect at 11.6 V. Data were taken for four cycles but the average of the last three cycles were taken for calculating charge dissipation up to the suggested low voltage disconnect (LVD). The maximum depth of discharge (DOD) at LVD was calculated by dividing the charge dissipated up to the LVD by the total charge dissipated by the battery up to fully discharged voltage at 10.5 V. Average depth of discharge at LVD was calculated by taking the average of DODs at LVD of the last three cycles. Equation 1 was used to calculate the maximum depth of discharge at LVD at constant current.

$$DOD_{\mathrm{LVD}} = \left(\int_{t_{\mathrm{d,s}}}^{t_{\mathrm{d,LVD}}} I_d \mathrm{d}t \Big/ \int_{t_{\mathrm{d,s}}}^{t_{\mathrm{d,C}}} I_d \mathrm{d}t \right) 100 \qquad (1)$$

where, I_d is discharge current (A), $t_{\mathrm{d,s}}$ is the start time of discharging (hr), $t_{\mathrm{d,LVD}}$ is the time when the battery is discharged up to low voltage disconnect (hr) and $t_{\mathrm{d,C}}$ is the time when the battery is discharged completely (hr).

2.4 Tests on charge controllers

The charge controller controls the charging and discharging of the battery and thus prevents the battery from deep discharging and overcharging. In standalone systems, a charge controller provides protection to the loads from short circuits and over-current faults. Proper and intelligent use of the charge regulator ensures longer life of the system. It also protects the battery from discharging through the photovoltaic panels at night when there is no sunlight. Poor quality charge controllers reduce the energy storage capacity and consequently the service time in terms of electricity supply. The design of charging control system however requires a good understanding of the dynamic behavior of the battery [40]. Lead-acid batteries, typical in Bangladeshi SHS installations, are particularly prone to damage by poor charging control. The following tests were performed to assess the performance of the charge controllers (N = 24) from six manufacturers.

2.4.1 High and low voltage disconnect tests

IDCOL approved technical specifications recommend the use of charge controllers/regulators based on voltage control. For the fixed voltage charge controller, the recommended high voltage disconnect (HVD) is 14.3$\pm$0.2 V and low voltage disconnect (LVD) is 11.6$\pm$0.1 V [23]. To determine the HVD, the solar panel was simulated by a voltage source by limiting the current. Another voltage source; i.e., a voltage divider circuit with two batteries connected in series, was connected to the battery terminal. Battery voltage was increased from 12 V and the charging indicator/indicators were observed at the same time. The voltage reading was observed and recorded when the charge controller disconnected the panel terminal (for series controller) or short circuited the panel terminal (for shunt controller).

For determining the low voltage disconnect, standard loads (fluorescent lamp) were connected to the load terminal of the charge controller while a power source (battery with a voltage divider circuit) was connected to the battery terminal. The voltage of the source was reduced from 13 V and were observed and recorded when the charge controller disconnected the loads from the battery. Once the loads are disconnected from the battery by the charge controller due to low battery voltage, the voltage of the battery increases gradually. A higher reconnect voltage (after disconnect due to low voltage) than LVD is, therefore, required to avoid the oscillation of the loads due to the rise and fall of battery voltage. The reconnect voltage for the charge controller in Bangladesh is specified as 12.6 ± 0.2 V [23].

2.4.2 Self power consumption of the charge controller

Self power consumption of a charge controller is defined as the current consumed by the charge controller when connected to the battery and all loads are disconnected. As per IDCOL technical specifications, the maximum current drawn by a charge controller should not exceed 20 mA when no LEDs are lit. Due to the sealed construction of the tested charge controllers it was not possible to turn off all the LEDs, without altering their characteristics. To determine self power consumption, the battery terminal of the charge controller was connected to a voltage source whereas the panel and load terminals were left open. A high precision voltmeter, along with a shunt (low resistance) was used to measure the voltage and current of the charge controller respectively. The voltage of the power supply was varied from the load off condition (below LVD) to high voltage disconnect (HVD) and meter readings were observed. The maximum power consumed by the charge controller within this voltage range was recorded as self power consumption.

2.4.3 Reverse current leakage protection

Reverse current leakage protection prevents the battery from discharging through the photovoltaic panel when there is no light to generate electricity by the panel. To test for reverse current leakage protection, the charge controllers were connected to the battery and the panel terminals of the charge controller were short circuited to observe whether current flowed in the reverse direction.

2.4.4 Reverse polarity protection

This form of electronic blocking is an essential feature of a charge controller as it offers protection for reverse polarity connection to the battery. The following tests were performed on reverse polarity protection:

- Battery connected in the battery terminal of charge controller in reverse polarity keeping the load and panel junction open; and
- Battery connected in the battery terminal of charge controller in reverse polarity with the panel and some loads connected.

2.4.5 Input and output short circuit protection

For input short circuit protection test, the charge controller terminals for the solar panel were short circuited while the battery was connected to the battery terminal. An ammeter was placed in the battery terminal to observe whether extra current, in addition to the self power consumption of the charge controller, was drawn from the battery during the short circuit.

For output short circuit protection test, the charge controller terminals for the load were short circuited while the battery was connected to the battery terminal. This is a destructive test as the short circuit renders the charge controller unusable if it is not provided with a protection.

2.5 Lamp circuit (inverter)

Typically, 10 W, T8 fluorescent tube lamps are used in Bangladeshi SHS program. The fluorescent lamps are forced to draw reduced power in the range of 6–8 W. Inverter or lamp circuits from five approved manufacturers along with the lamp were collected for lab tests. Following specifications were observed and tested for the compliance with the standards [23].

2.5.1 Operating voltage

Each lamp was connected with a variable DC voltage source, the voltage of which was varied between disconnect voltages; i.e., 11.5 V to 14.5 V, to observe the operation of the lamp circuits in this range.

2.5.2 No load protection

When an inverter is connected to the battery without a fluorescent tube lamp; i.e., load, high voltage appears in the output of the inverter. This high voltage formation, due to the absence of a load, can damage the circuit within few seconds if no protection is offered. For this test, lamp circuits were connected to the power supply without lamps for two minutes to observe whether the inverter circuit can withstand the high voltage of the output terminal.

2.5.3 Operating frequency

To test whether the operating frequency of the lamp circuits is greater than 20 kHz within the operating voltage range, the lamp circuit, along with the fluorescent lamp (load) was connected to the power source. The output voltage of the lamp driver circuit (inverter) was observed using a digital storage oscilloscope (DSO), to determine the operating frequency of the lamp circuit.

2.5.4 Electrical waveform

The electrical waveform of the lamp circuit terminal should be symmetrical in time to within a tolerance of 10% over the voltage range of 1.51-14.5 Vdc. The asymmetry of the waveform was determined from the data taken from the DSO.

2.5.5 Crest factor of the voltage waveform

The maximum crest factor is specified to be at least two in the IDCOL specifications. Crest factor is the ratio between peak amplitude and root mean square (RMS) of the waveform, calculated using Equation 2.

$$C = \frac{|x|_{\text{peak}}}{x_{\text{RMS}}} \tag{2}$$

where, C is the crest factor (-), $|x|_{\text{peak}}$ is the peak amplitude (-) and x_{RMS} is the RMS value of the waveform (-).

2.5.6 Efficiency

A voltmeter was used in this test to measure the input voltage and current with the help of a shunt resistor. A DSO was used to determine the high frequency output voltage and current. For the latter, a very low resistance was used in series with the circuit. The output current, voltage and power of each inverter was calculated form the output data using a Matlab [41] program. The efficiency of the inverter was calculated by dividing the output power by the input power. This test was performed for both disconnect voltages: LVD and HVD. According to the IDCOL specifications [23], the efficiency of the inverter needs to be more than 80% in the operating voltage range.

2.5.7 Reverse polarity

If lamp circuits are connected in opposite polarity it reverses the biasing of the electrical component, which can damage the circuit. A protection diode is typically used in the input of the lamp circuit to protect it from reverse biasing. Reverse polarity is tested in this research by connecting a voltage source, capable of supplying the rated voltage in reverse polarity to the lamp circuit. It was observed whether the lamp circuit could withstand this connection.

3 Results and discussion

3.1 PV Panels

3.1.1 Capacity

Results from the capacity test of PV panels are given in Figure 3. The binding IDCOL specification only allows panels with positive tolerance. Out of the 123 panels tested, 94 (76.4%) were found to have power rating equal to or more than the rated. Greatest percentage difference was found for a 15 Wp unit, the actual capacity of which was 21.1 Wp, representing 40.5% more capacity than the rated. Higher percentages (>20%) of positive tolerance were mostly found for panels with a low rating, typically less than 40 Wp. Overall, standard deviation of the difference in capacity among panels with higher actual capacity was 8.02%.

29 (23.6%) panels were found to have power rating less than the rated. One of the panels that failed the capacity test had 26% lower capacity (48.1 Wp) than the rated (65 Wp) and originated from

outside Bangladesh. Of the twelve local panels from four manufacturers, three panels (25%) were found to be of capacities less than the rated. In comparison, 26 (23.4%) of the tested panels of international origin were found to be less than the rated. The difference between local and international appears to be insignificant considering the differences in the number of panels tested. Overall, standard deviation of the percentage difference in capacity among the failed panels was 5.17%.

< Figure 3 is about here>

3.2 Battery

3.2.1 Capacity

Normalized capacities of tested batteries are illustrated in Figure 4. The actual capacity of batteries from manufacturers A and C is higher than their rated capacities. In contrast, the capacity is lower than the rated for manufacturers B and D, except in one case (B1) where the capacity is slightly higher (100.5%).

<Figure 4 is about here>

The performance of the batteries of capacities 80 and 55 Ah (B3, B4, B5) of manufacturer B is very poor, with the average capacity close to 70% of the rated. A field study of randomly inspected 60 systems in Bangladesh shows that majority of the SHS packages under operation in Bangladesh uses 55Ah (25%) and 80 Ah (35%) batteries [42]. Manufacturer B produces the batteries which are less (80%) than the rated capacities. The capacity of a battery depends the active materials used. Sponge lead (Pb), lead peroxide (PbO_2) and dilute sulfuric acid (H_2SO_4) are commonly used active materials in the Bangladeshi SHS market. It is evident that the manufacturer B provides less active materials in the electrodes, especially for the batteries B3, B4 and B5. The price of lead has increased significantly over the past years, from around 500 US$/t in 2000 to the current price of around 1800 US$/t, peaking at around 3720 US$/t in 2007.[7] Increase in the cost of materials may have been the reason for reducing the amount of active materials. On the other hand, manufacturer A produces much higher capacity batteries. This indicates that both the manufacturers are marketing products of inferior quality.

Discharge profiles of tested batteries are illustrated in Figure 5. It is evident that manufacturer B provides batteries of two different standards. Half of its batteries suffer from very low capacity which are significantly less than the rated capacity. Both the quantity and quality of materials have an impact on the profiles, in particular for B3, B4 and B5, in particular the rate of voltage drop between 0 and 6 hours. Similar rates can be seen for D1 and D2 for the hours between 0 and 8. Sub-par batteries have

[7] Index prices of metals and other materials vary slightly between markets. Historical prices can be obtained from Index Mundi (http://www.indexmundi.com) and London Metal Exchange (http://www.lme.com)

also been found to degrade faster than designed that has the potential to negatively affect consumer satisfaction [43]. It is, therefore, imperative to ensure the quality of batteries to achieve the designed performance of the whole system.

<Figure 5 is about here>

3.2.2 Specific gravity of the electrolyte of charged and discharged batteries

The specific gravity of the electrolyte of charged and discharged batteries varies from manufacturer to manufacturer, as shown in Figure 6. The specific gravity of fully charged and discharged batteries from manufacturers A and C varies within the range: 1.232–1.196 and 1.148–1.129 respectively. Batteries of manufacturer A work with the largest change in electrolyte densities (84 g/l) whereas batteries of manufacturer B work with the smallest change in electrolyte densities. The higher specific gravity changes with charging and discharging conditions imply that the battery’s combination of electrode material and the quantity of electrolyte are optimum. Batteries of manufacturer C operates in lower specific gravity whereas those from manufacturer A operate in the highest specific gravity. The difference in specific gravity of batteries form manufacturer B (B3, B4, B5) is small, meaning that there are less active electrode materials compared to the electrolyte, which may affect the batteries during operation.

<Figure 6 is about here>

3.2.3 Depth of discharge (DOD) at low voltage disconnect

The results of this test are illustrated in Figure 7. DOD at low voltage disconnect of the batteries of manufacturers A, B and C ranges between 80% and 82%. DOD of batteries from manufacturer D reaches 88% of DOD. As the cycle life of a battery depends on the usage of the battery’s DOD, the fixed voltage LVD is not suitable for every battery. It is suggested that the DOD can be fixed by changing the properties of the individual batteries or by using adaptive charge controllers. The latter may increase the price of the system at the beginning but in the long run it will provide longer life of the batteries, which will be more beneficial and economical considering the difference in the component lifespan between a battery and a charge controller.

<Figure 7 is about here>

3.3 Charge controllers

3.3.1 Low and high voltage disconnects

Charge controllers from manufacturers I, J and K have both the LVD and HVD within the limit specified by IDCOL [23], as shown in Figure 8. Majority of the charge controllers (75%) of manufacturers G and H are within the specified limit. However, one charge controller of the manufacturer H has HVD higher than the specified maximum but the other three are within the specified range. Both the LVD and HVD of charge controller from manufacturer L are less than the specified limits. Manufacturer G produces charge controllers with much lower LVD than the specifications allow. Therefore, only half of the manufacturers produce charge controllers satisfying specifications for both LVD and HVD. The charge controllers of the manufacturer G are widely used in the market and in particular by the market leading partner organization that accounts for more than half of the SHS installations in Bangladesh [42].

<Figure 8 is about here>

3.3.2 Self power consumption

Results from self power consumption test are provided in Figure 9. The specified self power consumption of a charge controller should not be more than 20 mA in the operating voltage range [23]. Manufacturers G, J and K produce charge controllers with self power consumption within the limit. Charge controllers of manufacturer H, I and L have much higher self power consumption. It is observed that charge controllers that use electromagnetic relay instead of MOSFETs for connect and disconnect operations have higher self power consumption.

<Figure 9 is about here>

3.3.3 Reverse current leakage protection

All the charge controllers have the reverse current leakage protection, this protection is provided by inserting a diode, D1, in the charging circuit of the charge controller, as shown in Figure 10 and 11.

<Figure 10 is about here>

<Figure 11 is about here>

3.3.4 Reverse polarity protection

All the charge controllers' input MOSFETs were burnt as soon as the battery was connected in reverse polarity, except for the charge controller from manufacturer I. However, this manufacturer's MOSFET was also burnt when the panel was connected.

All charge controllers used in the solar home systems in Bangladesh use the shunt topology to protect overcharging by using a MOSFET in parallel to the panel. When the battery is charged (at HVD), the MOSFET (Q1) is switched on by the control circuit and it drains the generated power, as in Figure 10. Therefore, when the battery is connected in reverse polarity, the battery is short circuited by the intrinsic diode of the MOSFET Q1.

The manufacturer I provides an extra MOSFET (Q2) in series with the panel and battery, as shown in Figure 11. The MOSFET Q2 is on when the panel is connected and generates power. Therefore, the charge controller provides reverse polarity protection when no panel is connected. However, as soon as the panel is connected and it generates power, current flows through the intrinsic diode in Q1. The MOSFET Q2 is then switched on by the power from the panel resulting in the flow of short circuit current which burns the MOSFETs. It can, therefore, be concluded that none of the charge controllers provide protection from reverse polarity.

3.3.5 Input and output short circuit protection

All charge controllers have input short circuit protection. In fact, all of them have the reverse protection diode inside the charge controller. The diode acts as the input short circuit protection. All charge controllers, except those from manufacturers H and J have output short circuit protection. According to the SHS technical specifications, both input and output short circuit protections are required in the charge controller. It is evident that charge controllers from manufacturer H and J do not comply with the specifications set for SHS in Bangladesh.

3.3.6 Summary

Table 4 summarizes the tests carried out on 24 charge controllers from six most popular manufacturers. It is evident that none of the charge controllers meet all the criteria as set out in the approved SHS specifications in Bangladesh.

<Table 4 is about here>

3.4 Fluorescent lamp circuit (inverter)

3.4.1 Operating voltage

All tested lamp circuits perform normally within the operating voltage range (11.5 –14.5 V). The illumination is better with an increase in voltage. The fluorescent lamps used in SHSs in Bangladesh are all rated 10 W but are forced to operate in low power, between 6 and 8 W.

3.4.2 No load protection test

All inverter circuits connected to the battery without the lamp sustains for two minutes without load.

3.4.3 Operating frequency

The operating frequency of the lamp circuits should be more than 20 kHz within the operating voltage range. Test results show that lamp circuits from all the manufacturers are above the specified operating frequency range and they comply with the standard. As shown in Figure 12, all lamp circuits operate at a much higher frequency than the specified minimum. The variation of frequency due to voltage change was minimal.

<Figure 12 is about here>

3.4.4 Electrical waveform of the fluorescent lamp circuit

The asymmetry of the electrical waveform of the lamp circuits from all manufacturers are within the specified limit; i.e., the asymmetry of the voltage waveforms was within 10% over the voltage range of 11 to 12.5 Vdc, as shown in Figure 13.

<Figure 13 is about here>

3.4.5 Crest factor of the voltage waveform

The ratio of maximum peak to RMS voltage of the waveform (crest factor) applied to the fluorescent lamp circuit (inverter) should be less than two, as specified in the IDCOL specifications. A digital storage oscilloscope was used to observe the voltage waveform of the lamp circuit's output. From the storage data a Matlab program was used to regenerate the wave shape. The electrical wave shape and the crest factor was observed and calculated both for HVD and LVD voltages. Figure 14 shows the comparison of crest factors of lamp circuits of different manufacturers. At LVD all manufacturers except T produces lamp circuits with a crest factor less than two. But at HVD, manufacturers R and T does not satisfy the criteria.

<Figure 14 is about here>

The value of the crest factor for an ideal sinusoidal waveform is 1.44. A crest factor close to a sinusoidal wave is better for the fluorescent tube lamp. The higher crest factor and low voltage operation is responsible for the end blackening of the fluorescent tube lamp [44]. Voltage wave shapes of higher crest factor is responsible for the lower service life of the fluorescent lamps used in the SHS [45]. The Crest Factor for SHS is suggested to be less than 1.7 in different literature [29, 45]. However, the Bangladeshi specifications suggest a value of two.

3.4.6 Inverter efficiency

The efficiency of the inverter circuit is very important as solar power with battery back up is expensive. The ratio of power supplied to the fluorescent lamp of the inverter's output to the dc power supplied to the inverter circuit is defined as the efficiency of the lamp circuit. The luminous efficacy of a lamp can be higher if an energy efficient inverter circuit is used, although the former depends on the quality of the lamp as well. The more efficient the lamp inverter circuit is, the more is the energy saving potential of the lamps. The specifications suggest that the inverter efficiency of the lamp must be greater than 80% in the operating voltage range [23].

Efficiency of tested lamp circuits at low voltage disconnect and high voltage disconnect is given in Figure 15. Lamp circuits from manufacturers S and T comply with the efficiency standard in the operating voltage range. Manufacturer Q complies only in the HVD voltage. Manufacturer P and R do not comply the efficiency criteria in the operating voltage range. Generally, the fluorescent tube lamps are operated at night when the battery voltage is near to the LVD voltage. Therefore, the efficiency at LVD is more important than HVD. For this reason, it can be concluded that the inverter from manufacturer Q also does not comply with the IDCOL standard.

<Figure 15 is about here>

3.4.7 Reverse polarity protection

Manufacturers Q and S do not provide reverse polarity protection; however, lamp circuits from the other three manufacturers provide the reverse polarity protection. The circuits got damaged as soon as the power line is connected to the battery input terminal in reverse polarity.

3.4.8 Summary

Table 5 summarizes tests carried out on ten lamp circuits from five most popular manufacturers. It is evident that none of the lamp circuits meet all criteria as per approved specifications for SHS program in Bangladesh.

4 Recommendations

In light of the findings of this research, the following recommendations are made for implementation by the SHS program management. Countries, in particular, the developing countries with similar legislative and governance structures looking to implement an SHS program may also find these recommendations useful.

4.1 Introduction of stringent specifications

To a large extent, the success of the solar home system program in Bangladesh can be attributed to the technical specifications developed at the beginning [19]. The early installations were of superior quality and have performed well. The dynamics of the market appears to have changed with the growth in the industry and the suppliers are finding new ways to reduce cost at the expense of component quality. More stringent specifications need to be developed to take into account the findings from research such as this and the developments in the local market. For example, some of the tested batteries have much lower capacity than their rated value. The deviation in the capacity is prominent among the two of the four main battery manufacturers in Bangladesh. Both higher and lower capacity batteries are found, which are detrimental to the optimal operation of the system. Generally, the battery size is optimized with the connected load and the size of the panels. During operation the oversized batteries will seldom get the opportunity to be fully charged whereas the undersized batteries will not be able to store the energy produced by the panel and can never provide the expected energy to the loads; thereby affecting the designed autonomy of the system. In the case of charge controllers, both the charging and discharging were found to be less efficient than they should be. New specifications such as at least 90% efficiency for charging and discharging at rated current can be adopted. For the sustained growth and success of the program, it is essential that specifications are updated to a much stricter tolerance and more frequently.

4.2 Optimal design and quality of components

Solar home systems are an important social engineering application in the sense that they often serve the marginalized sections of society whom typically do not have easy access to energy or capital.

Investments in an SHS at the cost of a few hundred US dollars, however small it may seem compared to other energy applications, is one of the larger investments they make. It is, therefore, essential that they get their return on investment through the smooth operation of the system and that it does not require a lot of maintenance. Design of the system needs to be optimized for the needs of the consumer and the changing pattern of their energy use so that the systems are resilient to change. For example, systems need to adapt to the transition from fluorescent to low wattage LED luminaires. The ownership of devices may also change; e.g., from 2nd generation (2G) mobile phones to 3rd generation (3G) smartphones.

The quality of electronic components is another aspect that needs attention. In the case of charge controllers, this research found the use of very low grade diodes with higher forward voltage as blocking diode at the panel terminal of the charge controller, which reduces charging efficiency. In addition, some manufacturers provide low quality switching devices at the load terminal of the controller to connect loads with and disconnect from the battery, which reduce discharging efficiency. Another example is the use of electro–magnetic relays in charge controllers resulting in much higher self power consumption. Because of the relatively small size (<50 Wp) of the majority of installations, it is necessary to incorporate solid state switches in the design to reduce self power consumption and increase the overall efficiency of the system.

The gap between designed and actual performance is a concern in energy applications and the SHS market is no different. The quality of components is one of the most important factor responsible for the deviations from the designed performance. Very little is done to account for the lack of quality during design stages predominantly because of the use of deterministic specifications [23] and design methods that are inadequate to deal with the stochastic nature of factors affecting performance. Apart from manufacturing quality, as discussed in §3.2, the variations in the environmental factors such as ambient temperature have a significant impact on the performance of the key components of an SHS, which are seldom considered in the design of small systems. The lack of maintenance, the use of lower quality materials and user behavior are some of the other factors that can contribute to sub-par performance of the system and are challenging to consider during design.

4.3 Better consumer rights protection

It is evident from this research that there is a general lack of regard for consumer rights among the suppliers and manufacturers of SHS components. This finding also agrees with the previous research on field–based assessment of technical quality of the Bangladeshi SHS program [19]. Despite the fact that Bangladesh has various institutional bodies such as standards and testing institutions to safeguard the quality of consumer products, there is an identified gap in the development of policies and legislations to better protect consumer rights [46]. In addition to quality assurance, the value of warranties to consumers is a concern, as reported by for the Kenyan market [47] where rural households were unable to assess the quality of PV modules and the buyers did not have faith in the vendors for honoring the stated warranties. It can be argued that access to energy is so important for Bangladeshi consumers, in particular those living in off–grid locations, that they are somehow compelled to purchase the SHSs that are available to them despite their substandard quality. Although this research did not investigate whether the consumers were aware of under–performing components but research into the behavior of Bangladeshi consumers about other products such as food [48] suggests that they purchase sub-standard products primarily due to the lack of available alternatives. There is an immediate need for the introduction of consumer rights protection law dealing with the supply of substandard components. The development of such legal instruments can have a wider scope and greater impact on sustainable development. However, care should be taken so that the regulation does not become excessive, which typically tends to raise cost and inhibit private sector development [49].

4.4 Introduction of a quality assurance mechanism

None of the charge controller and lamp circuit manufacturers produce components meeting the approved specifications for the SHS program in Bangladesh. Same is also true for some of the battery manufacturers and also PV panel suppliers/manufacturers. This research found that the tested models of components gained approval prior to industrial production from approved laboratories by meeting the criteria set out in the IDCOL technical specifications. It is evident that component specifications were changed after approval and in some cases lower quality materials were used during production without subsequent approval from the accrediting body. To counter this malpractice, it is necessary to introduce a robust testing and quality assurance framework that will take into account in-use quality for certification and approval. Punitive measures can also be integrated in such frameworks to discourage malpractice. There is a real risk of the erosion of consumer confidence in the technology if a transparent and robust quality assurance framework is not implemented immediately.

4.5 Training and education of stakeholders

The successful implementation of a robust quality assurance framework depends largely on the skills of professionals and the level of education and/or training of the stakeholders. In addition, raising the awareness of the consumers about quality and operation of the system can also have a positive impact on the SHS program. Discussions with various suppliers and manufactures during this research indicate a general need for more technical training, which needs to be investigated further in future. With regard to technical capability of the accrediting body, there is a need for more technically able staff at the field inspector level, in particular to bridge the gap between strategic and grassroots levels. Field inspectors can provide valuable feedback about system operation through random tests, which can contribute to the continual update of technical specifications.

5 Contributions and future work

This paper reports on the first comprehensive technical appraisal of the quality of key system components in one of the largest SHS markets in the world. The significance of this research lies in the key finding that none of the components, both local and international, meets all of the specified criteria which are there to safeguard the investments of 3.9 million families; i.e. 19.1 million people.[8] The research also identified issues related to manufacturing and system design, that resulted in: (a) a set of recommendations for updating guidelines and specifications based on evidence, and (b) the justifications for a better managed quality assurance framework combining manufacturing quality control and customer service. The findings are useful for the evidence-based evolution of SHS markets, not only in Bangladesh but also in the markets representing 1.2 billion people still without access to electricity.

Quality assurance and management is a multi-dimensional process that relies both on management practices and the environment supporting their use [50]. Quality assurance is also a continuous process. Future research can build on the work presented. Some of the proposed directions are as follows:

- Periodic evaluations of component quality at regular intervals need to be conducted to: (a) ensure quality and value for consumers, and (b) investigate the effects changes in policy, specifications, guidelines and implementation.
- Cross-country or market evaluations to investigate the factors affecting quality, focusing on the links between technical and socio-technical factors.
- SHS markets are dominated by non-governmental organizations (NGOs) [51] for whom social goals are as important as business goals. Their focus appears to be more on improving access than assuring quality. Research can be undertaken on (a) their practices on quality assurance, and (b) the development of a cost-effective quality assurance framework that can capitalize on their strengths of grassroots reach while addressing technical shortcomings.

6 Conclusions

This research investigated the technical quality of solar home system components: PV panel, battery, charge controller and lamp circuit or inverter. Test samples from market representative manufacturers and suppliers were collected for laboratory testing, which followed various local and international standards and guidelines.

Findings indicate that despite the overwhelming success of the SHS program in Bangladesh, system components are of inferior quality. None of the charge controllers and lamp circuits completely meet

[8] Household size in rural Bangladesh is 4.89 people. Source: Bangladesh Bureau of Statistics.

the criteria set out in the technical specifications. The efficiencies of the components are out of the specified range and the crest factor of the lamp circuit is beyond the tolerable limit. Batteries from the market leading manufacturer are of lower capacities, while some from other manufacturers are of much higher capacities than their nameplate rating – resulting in the sub–optimal operation of the system. In case of PV panels, 23.6% of the 123 tested panels have less than their rated capacities. Although the majority of the components are now locally made, most PV panels are still sourced from international markets – some from globally leading manufacturers. This research found that similar percentage of panels of both local and international origins failed the capacity test, suggesting no significant difference between the samples. The quality of component thus appears to have links with whether the market has legal protection of consumer rights and whether a robust quality assurance framework exists, as opposed to their origin or how reputable the manufacturer is.

The rapidly growing small–scale PV market in Bangladesh resulted in an explosive growth in the number of manufacturers and suppliers. The development of local industries and their contribution to the economy is laudable but at the same time there are evidence that most manufacturers are cutting cost by sacrificing technical quality of system components. Recommendations were made in this research to tackle under– performance: introduction of more stringent technical specifications; better design of the system; enhancing the quality of electronic components; training and education of field operators and inspectors; raising awareness of consumers; and most importantly, the implementation of a transparent and robust quality assurance framework. The success of the SHS program in Bangladesh now requires strong leadership to reduce the risk of the erosion of consumer confidence in this technology, which was pivotal for its success in Bangladesh when it evidently failed in a number of countries.

7 Acknowledgement

The authors would like to acknowledge the financial support received for this research from the World Bank via Infrastructure Development Company Limited (IDCOL). We are grateful for the support from our colleagues S. M. Raiyan Kabir and Moududul Islam for assisting in laboratory testing and investigation, and M Rezwan Khan for his advice. In addition, IDCOL partner organizations and equipment suppliers supported the investigation by providing samples and access to their premises.

References

[1] M. Mourshed, Pitfalls of oil-based expansion of electricity generation in a developing context, Energy Strategy Reviews 1 (2013) 205–210.

[2] N. Lior, Sustainable energy development: The present (2011) situation and possible paths to the future, Energy 43 (1) (2012) 174–191.

[3] EIA, International energy outlook 2011, US Energy Information Administration, Washington, DC, 2011.

[4] E. Wilson, D. Zhang, L. Zheng, The socio-political context for deploying carbon capture and storage in China and the U.S., Global Environmental Change 21 (2) (2011) 324–335.

[5] M. J. Bambawale, B. K. Sovacool, China's energy security: The perspective of energy users, Applied Energy 88 (5) (2011) 1949– 1956.

[6] S. V. Valentine, Emerging symbiosis: Renewable energy and energy security, Renewable and Sustainable Energy Reviews 15 (9) (2011) 4572–4578.

[7] World Bank, World development indicators (Edition: April 2011), World Bank, Washington, DC, 2011. doi:10.5257/wb/wdi/2011-04.

[8] IEA, Statistics: Indicators for 2013. Paris, France: International Energy Agency. https://www.iea.org/statistics/statisticssearch/report/ [Accessed: 17 April 2016]

[9] K. Kaygusuz, Energy for sustainable development: A case of developing countries, Renewable and Sustainable Energy Reviews 16 (2) (2012) 1116–1126.

[10] A. M. Dewan, Y. Yamaguchi, Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization, Applied Geography 29 (3) (2009) 390–401.

[11] M. Mourshed, The impact of the projected changes in temperature on heating and cooling requirements in buildings in Dhaka, Bangladesh, Applied Energy 88 (11) (2011) 3737–3746.

[12] SARI/Energy, Economic impact of poor power quality on industry: Bangladesh, South Asia Regional Initiative for Energy, New Delhi, India, 2003.

[13] A. Salman, Bangladesh's economy: Surrounded by deadly threats, International Journal of Social Economics 36 (1/2) (2009) 138–181.

[14] Power Grid Company of Bangladesh, Operational daily data, http://www.pgcb.org.bd/ (2012).

[15] MPEMR, Power System Master Plan (PSMP) 2010, Ministry of Power Energy and Mineral Resources, Dhaka, Bangladesh, 2010.

[16] MPEMR, Renewable energy policy of Bangladesh, Ministry of Power, Energy and Mineral Resource, Dhaka, Bangladesh, 2008.

[17] M. A. H. Mondal, M. Denich, Assessment of renewable energy resources potential for electricity generation in Bangladesh, Renewable and Sustainable Energy Reviews 14 (8) (2010) 2401–2413.

[18] REB, Line connection criteria, http://www.reb.gov.bd/ (2012).

[19] S. A. Chowdhury, M. Mourshed, S. R. Kabir, M. Islam, T. Morshed, M. R. Khan, M. N. Patwary, Technical appraisal of solar home systems in Bangladesh: A field investigation, Renewable Energy 36 (2) (2011) 772–778.

[20] P. Díaz, E. Lorenzo, Solar home system battery and charge regulator testing, Progress in Photovoltaics: Research and Applications 9 (5) (2001) 363–377.

[21] S. A. Chowdhury, S. M. R. Kabir, S. M. M. Islam1, S. Aziz, M. Mourshed, H.-G. Holtorf, K. Blum, Technical issues of solar home systems in rural Bangladesh: A post-installation survey, in: Proceedings of the Symposium of Small PV-Applications, OTTI, 2009.

[22] IDCOL, Infrastructure development company limited, http://www.idcol.org/ (2016).

[23] IDCOL, Technical Specifications for Solar Home Systems (SHS), Rural Electrification and Renewable Energy Development Project (REREDP), Infrastructure Development Company Limited, Dhaka, Bangladesh, 2005.

[24] M. Z. Baten, E. M. Amin, A. Sharin, R. Islam, S. A. Chowdhury, Renewable energy scenario of Bangladesh: Physical perspective, in: Proceedings of the 1st International Conference on the Developments in Renewable Energy Technology, United International University, Dhaka, Bangladesh, 2009, pp. 225 – 229.

[25] IEC, IEC 62509:2010: Battery charge controllers for photovoltaic systems: Performance and functioning, International Electrotechnical Commission, Geneva, Switzerland, 2010.

[26] IEC, IEC 60896–21:2004: Stationary lead-acid batteries – Part 21: Valve regulated types – Methods of test, International Electrotechnical Commission, Geneva, Switzerland, 2004.

[27] IEC, IEC 61215:2005: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval, International Electrotechnical Commission, Geneva, Switzerland, 2005.

[28] IES, Universal technical standard for solar home systems: Thermie B SUP 995-96, EC-DGXVII, Instituto de Energía Solar, Madrid, Spain, 2001.

[29] CNDRC, Solar Home Systems Implementation Standard, China National Development and Reform Commission, China, 2005.

[30] MEST, Nepal Photovoltaic Quality Assurance for Solar Home System, Ministry of Environment, Science and Technology, Kathmandu, Nepal, 2009.

[31] REREDP, Specifications for Solar Home Systems, Sri Lanka: Renewable Energy for Rural Economic Development Project, Colombo, Sri Lanka, 2004.

[32] IEC, IEC 60904–3:2008: Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data, International Electrotechnical Commission, Geneva, Switzerland, 2008.

[33] D. J. Spiers, A. D. Rasinkoski, Predicting the service lifetime of lead/acid batteries in photovoltaic systems, Journal of Power Sources 53 (2) (1995) 245–253.

[34] P. Ruetschi, Aging mechanisms and service life of lead acid batteries, Journal of Power Sources 127 (1-2) (2004) 33–44.

[35] A. Jossen, J. Garche, D. U. Sauer, Operation conditions of batteries in PV applications, Solar Energy 76 (6) (2004) 759–769.

[36] R. Wagner, Large lead/acid batteries for frequency regulation, load levelling and solar power applications, Journal of Power Sources 67 (1-2) (1997) 163–172.

[37] H. A. Catherino, F. F. Feres, F. Trinidad, Sulfation in lead-acid batteries, Journal of Power Sources 129 (1) (2004) 113–120.

[38] L. T. Lam, N. P. Haigh, C. G. Phyland, A. J. Urban, Failure mode of valve-regulated lead-acid batteries under high-rate partial-state-of-charge operation, Journal of Power Sources 133 (1) (2004) 126–134.

[39] F. Mattera, D. Benchetrite, D. Desmettre, J. L. Martin, E. Potteau, Irreversible sulphation in photovoltaic batteries, Journal of Power Sources 116 (1-2) (2003) 248–256.

[40] B. Huang, P. Hsu, M. Wu, P. Ho, System dynamic model and charging control of lead-acid battery for stand-alone solar PV system, Solar Energy 84 (5) (2010) 822–830.

[41] Mathworks, Matlab 2011a [computer software], The MathWorks Inc., Natick, MA, 2011.

[42] S. A. Chowdhury, S. M. R. Kabir, S. M. M. Islam, R. H. Siddique, A. T. M. G. Sarwar, Performance of solar home systems in rural Bangladesh, in: 1st International Conference on the Developments in Renewable Energy Technology, United International University, 2009.

[43] S. Komatsu, S. Kaneko, P. P. Ghosh, A. Morinaga, Determinants of user satisfaction with solar home systems in rural Bangladesh, Energy 61 (2013) 52-58.

[44] L. Narvarte, J. Muñoz, E. Lorenzo, Testing of fluorescent DC lamps for solar home systems, Progress in Photovoltaics: Research and Applications 9 (6) (2001) 475–489.

[45] F. G. Rosillo, Lifetime evaluation of DC-supplied electronic ballasts with fluorescent lamps for photovoltaic applications, Renewable Energy 29 (6) (2004) 961–974.

[46] Z. Andaleeb, A. N. M. A. Ali, The development of consumer protection law in Bangladesh: A critical comparative study, Independent Business Review 2 (1) (2009) 123–132.

[47] R. D. Duke, A. Jacobson, D. M. Kammen, Photovoltaic module quality in the Kenyan solar home systems market, Energy Policy 30(6) (2002) 477-499.

[48] M. M. Hossain, V. Heinonen, K. M. Z. Islam, Consumption of foods and foodstuffs processed with hazardous chemicals: A case study of Bangladesh, International Journal of Consumer Studies 32 (6) (2008) 588–595.

[49] F. Azmat, K. Coghill, Good governance and market-based reforms: a study of Bangladesh, International Review of Administrative Sciences 71 (4) (2005) 625–638.

[50] B. F. Flynn, R. G. Schroeder, S. Sakakibara, The impact of quality management practices on performance and competitive advantage, Decision Sciences 26 (5) (1995) 659-691.

[51] P. J. Balint, Bringing solar home systems to rural El Salvador: lessons for small NGOs, Energy Policy 34 (6) (2006) 721-729.

Figure captions

Figure 1: Solar home system installations in Bangladesh. Data source: IDCOL [22].

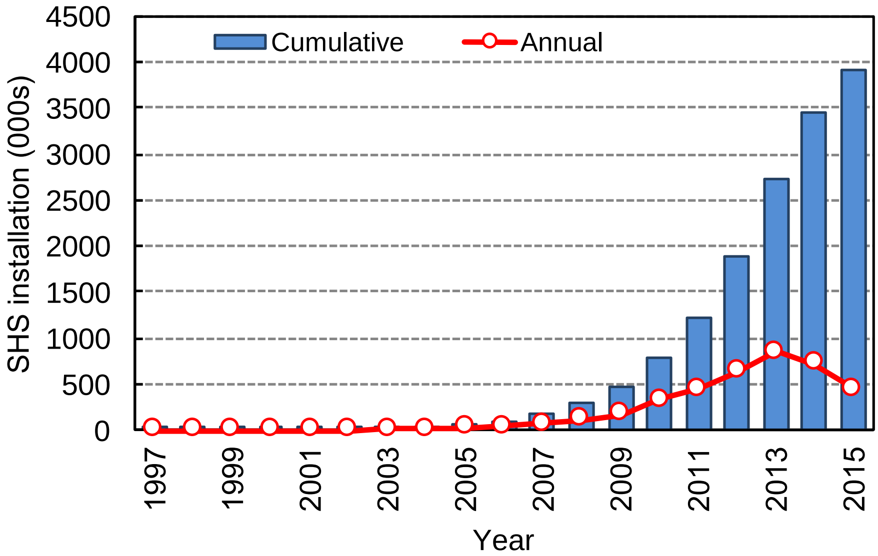


Figure 2: Components of a solar home system.

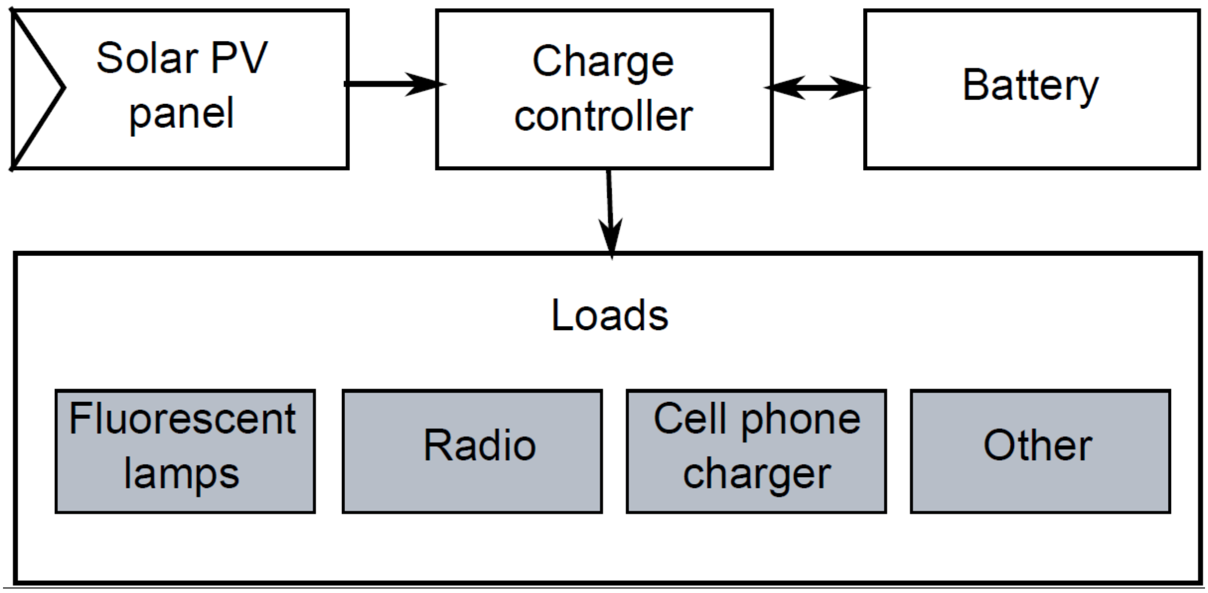


Figure 3: Rated vs. actual capacities of the tested PV panels and their differences.

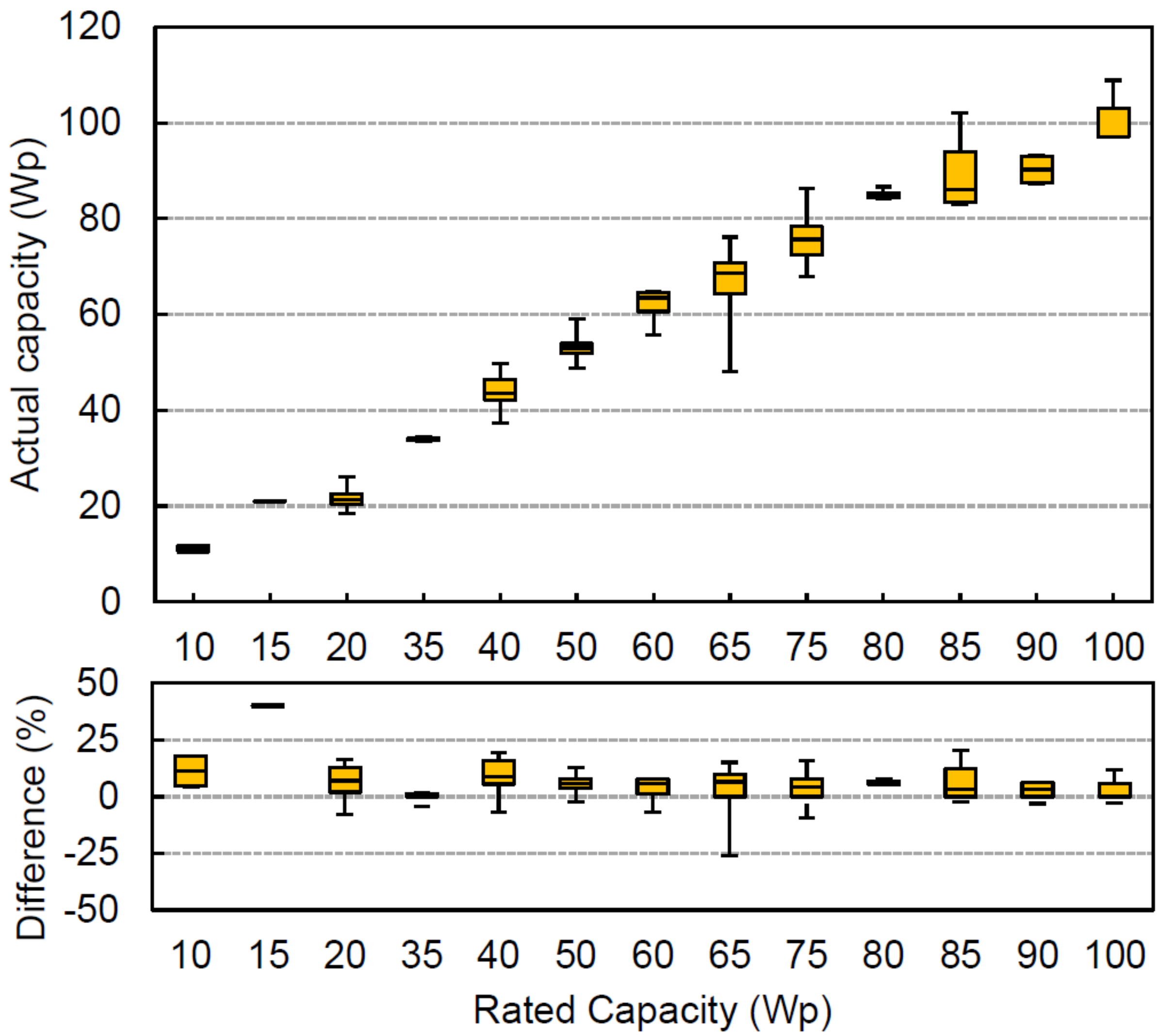


Figure 4: Normalized rated capacity of tested batteries.

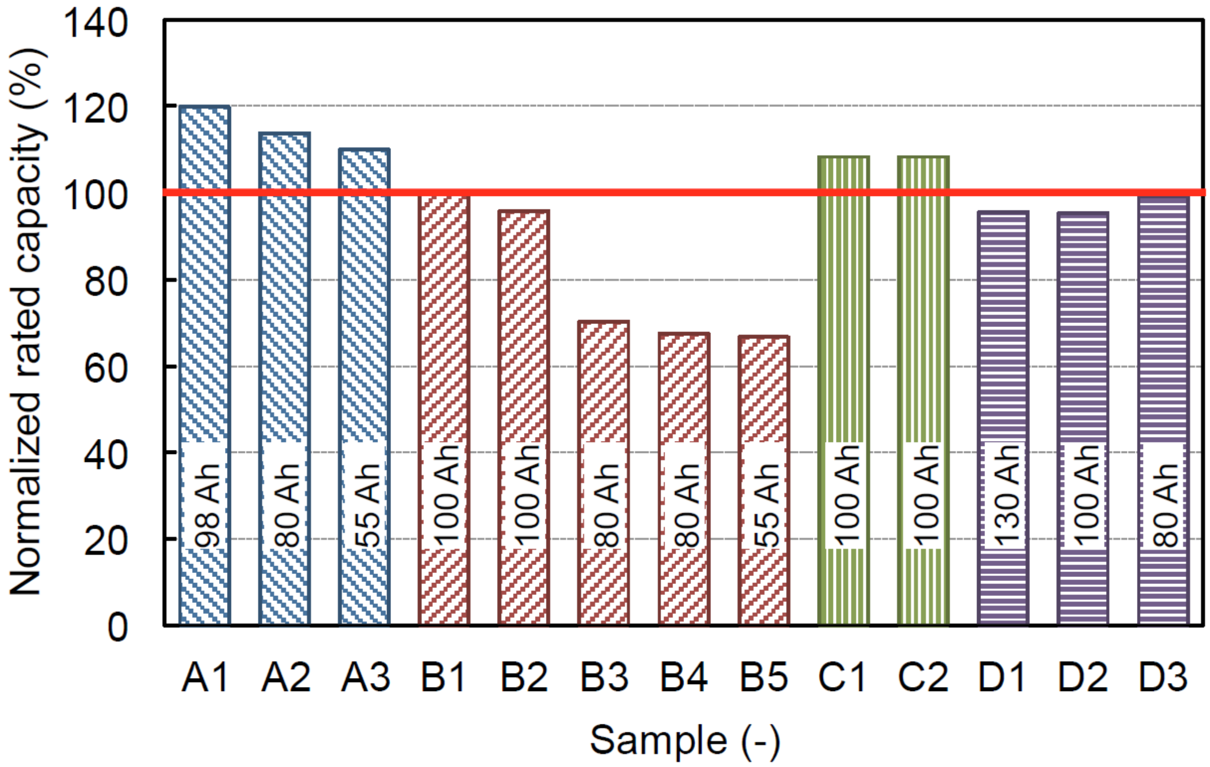


Figure 5: Discharge profiles of tested batteries.

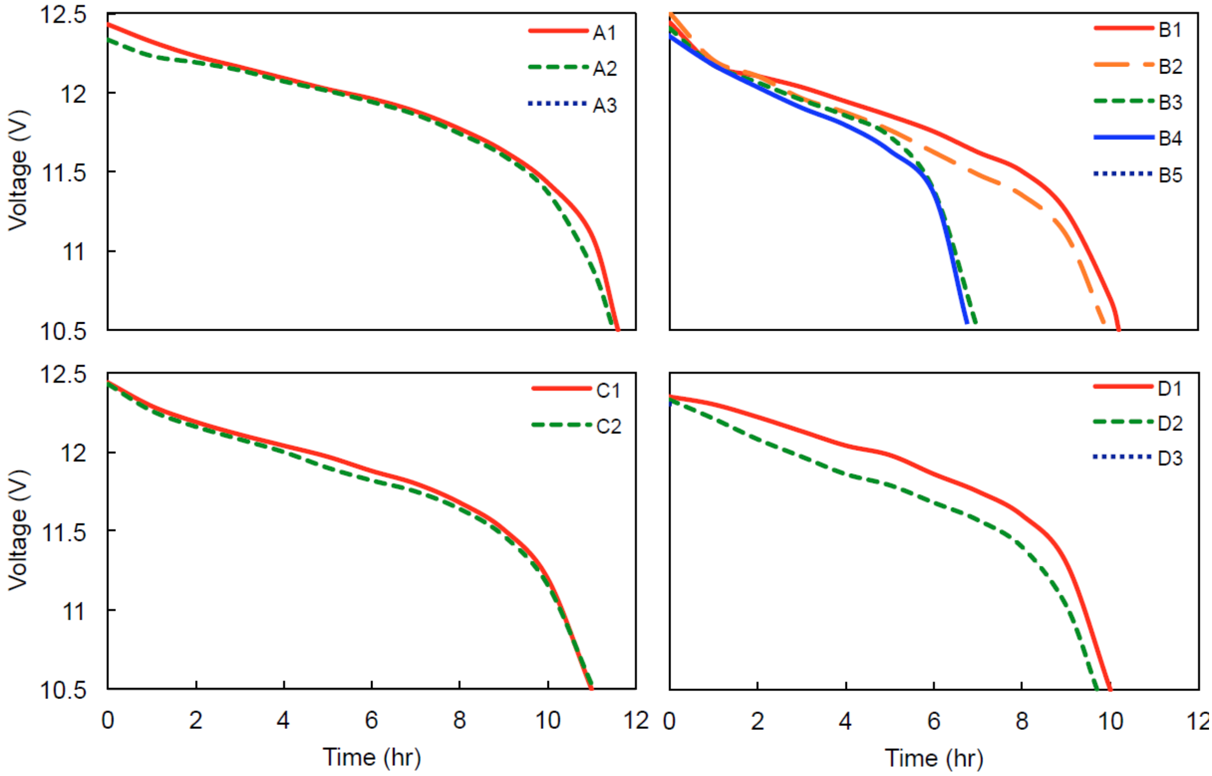


Figure 6: Specific gravity of the electrolyte of the charged and discharged states of the tested batteries.

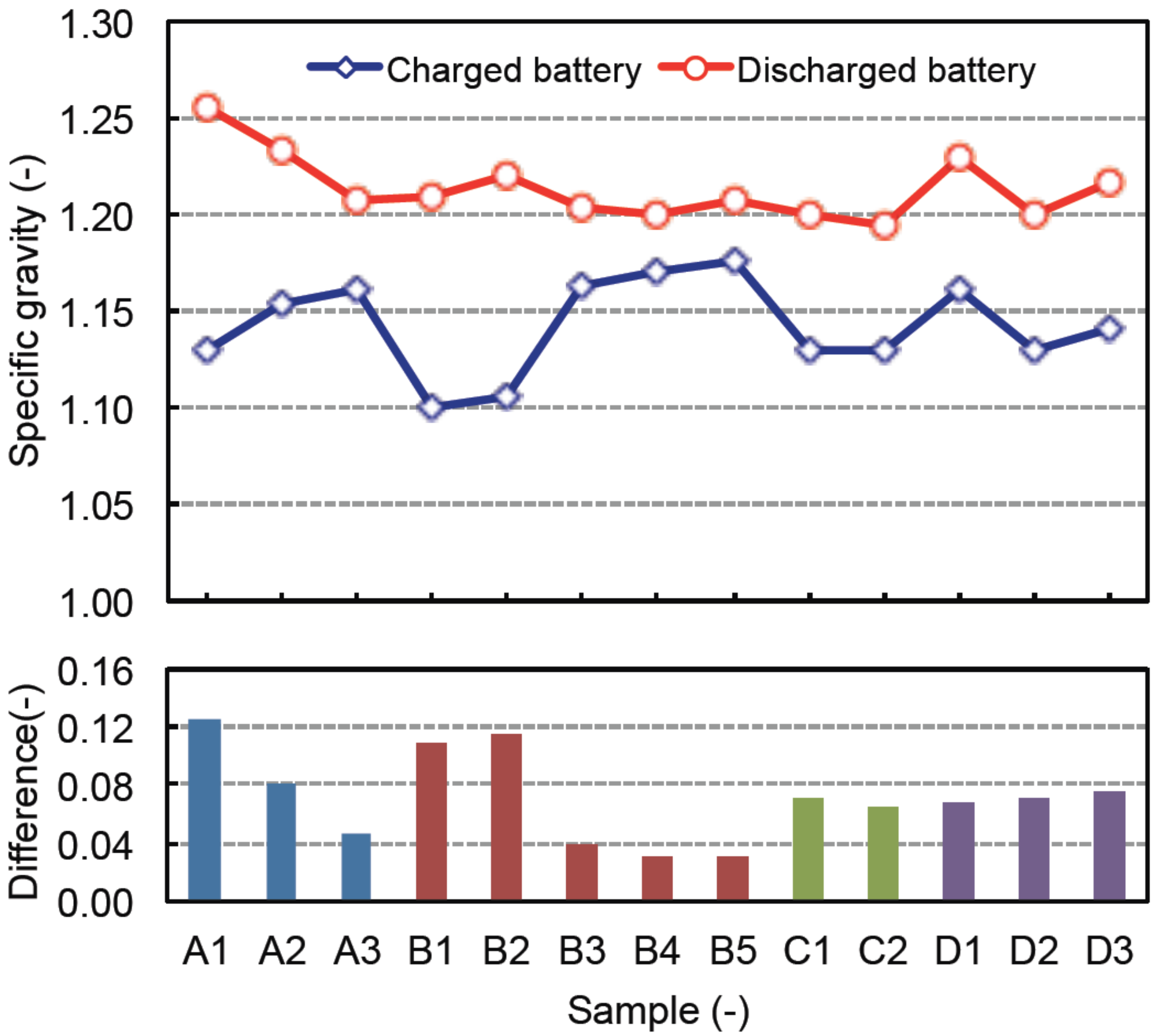


Figure 7: Depth of discharge (DOD) at low voltage disconnect (LVD) voltage.

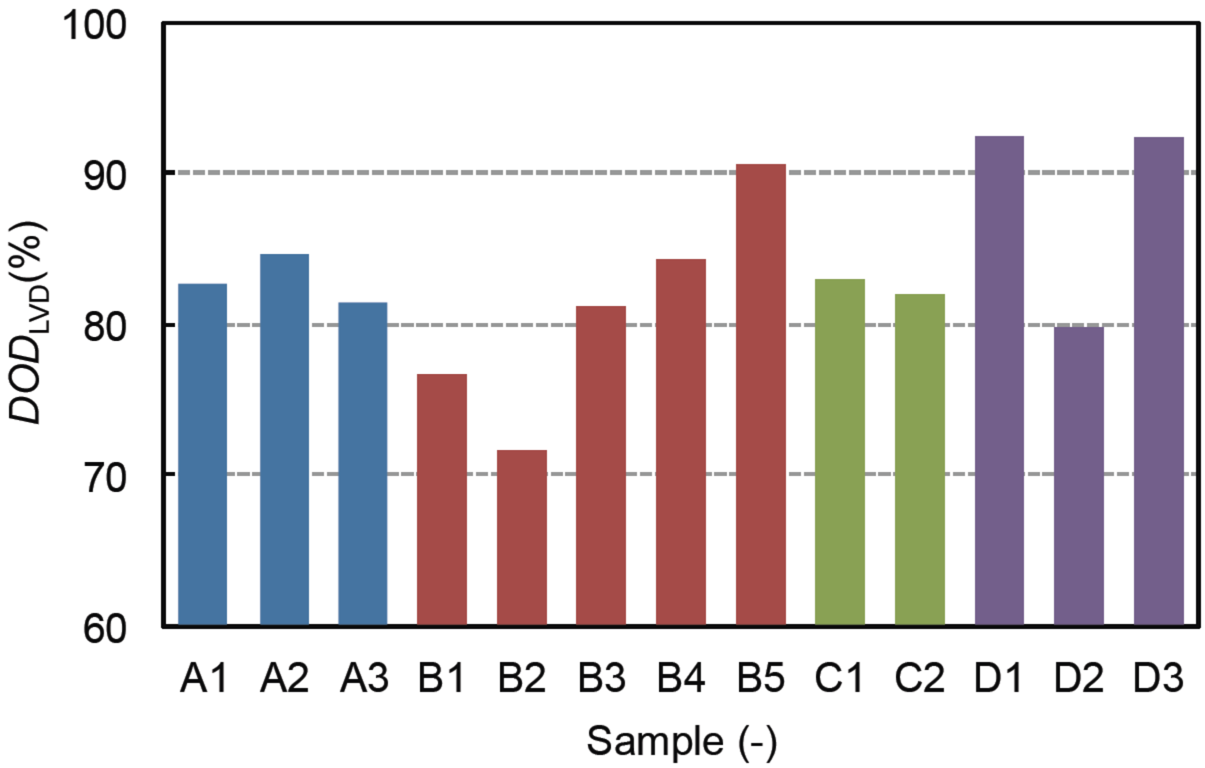


Figure 8: Low voltage disconnect (LVD) vs. high voltage disconnect (HVD) of the tested charge controllers.

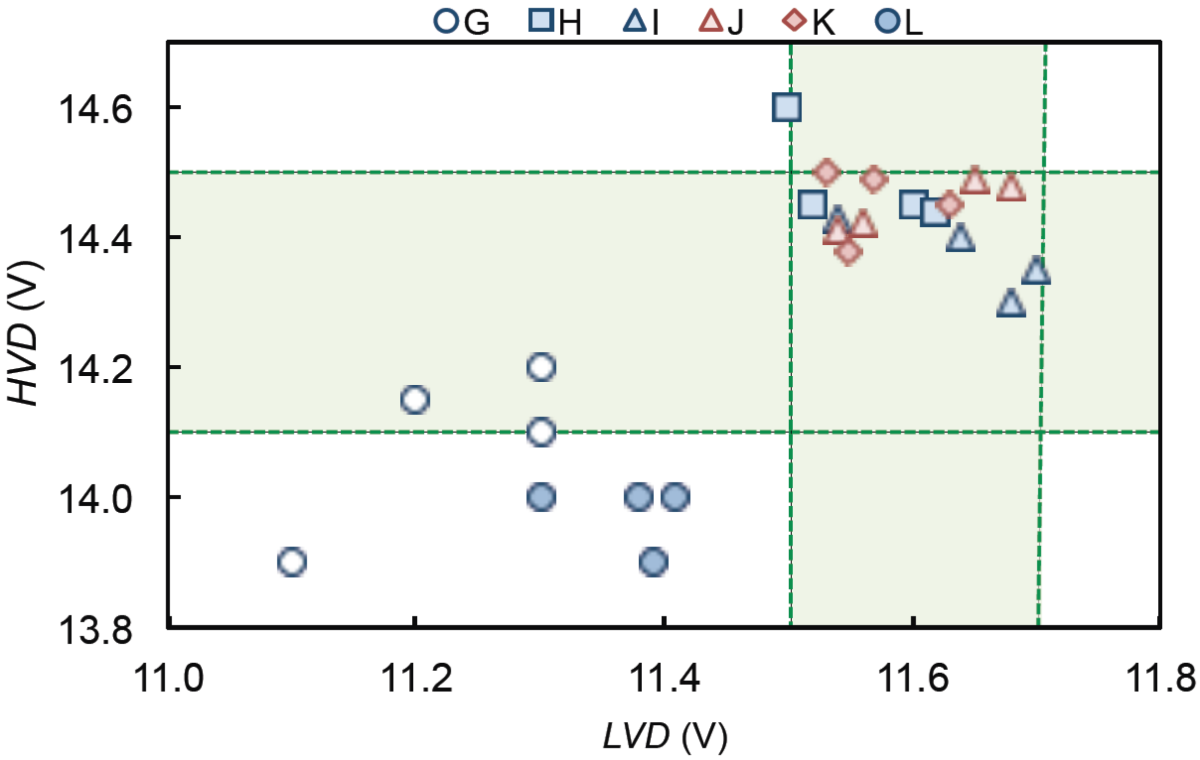


Figure 9: Average self power consumption of the tested charge controllers.

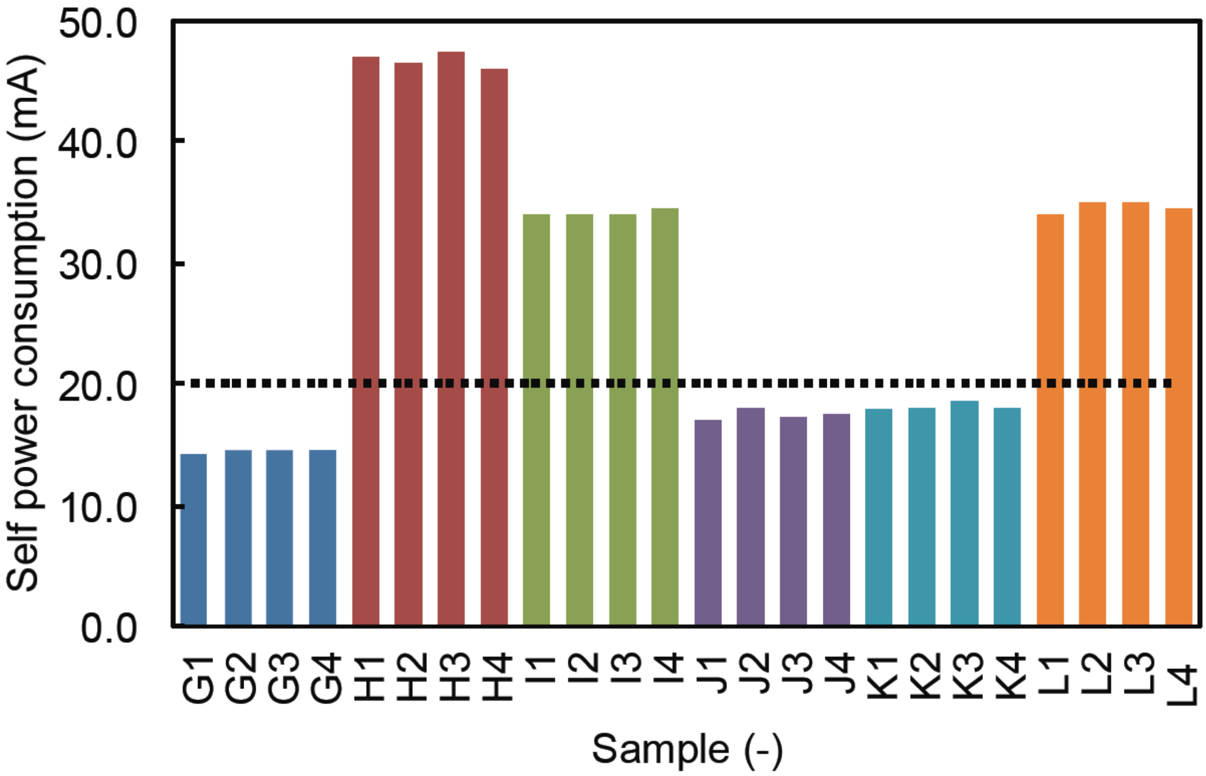


Figure 10: Partial charging circuit diagram of charge controllers from manufactures G, H, J, K and M.

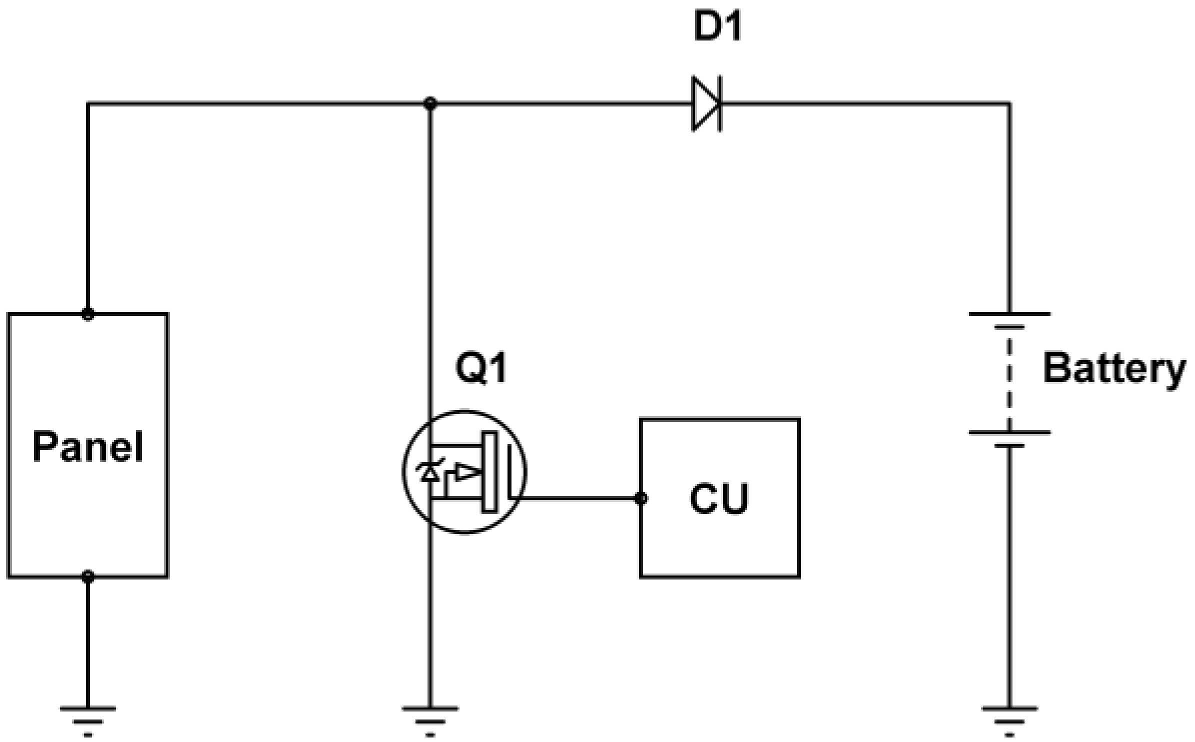


Figure 11: Partial charging circuit diagram of charge controllers from manufacturers I.

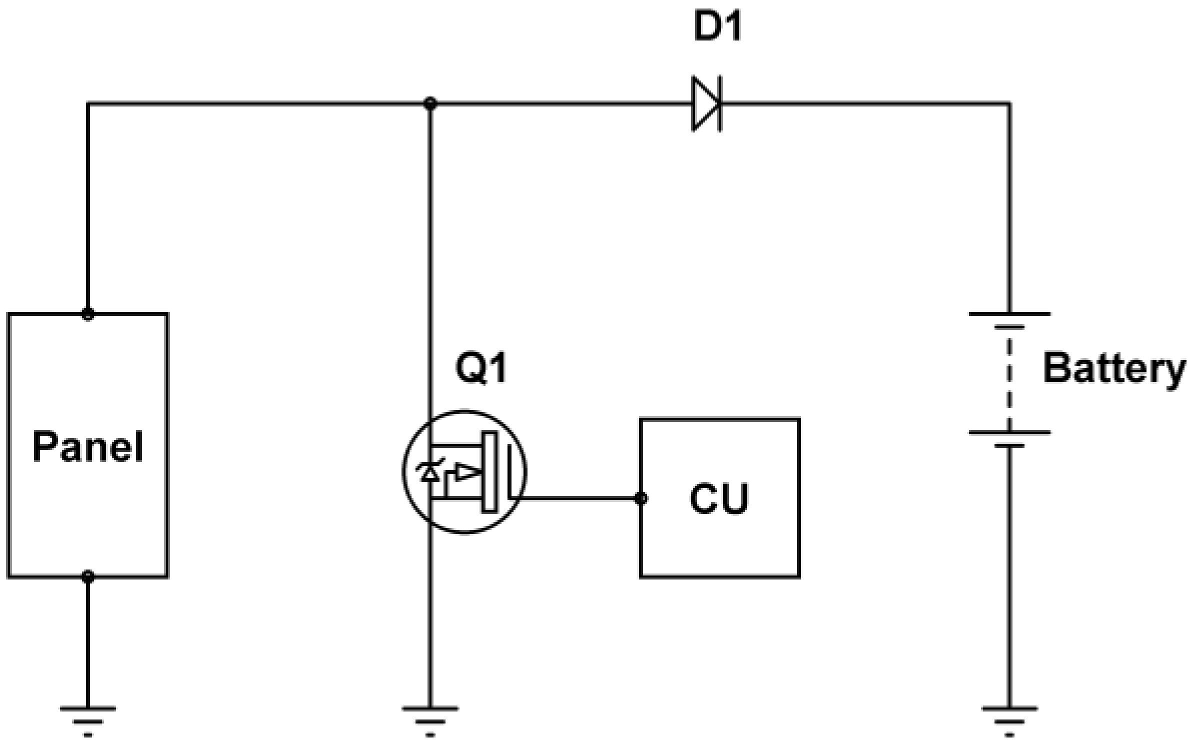


Figure 12: Operating frequency of tested lamp circuits.

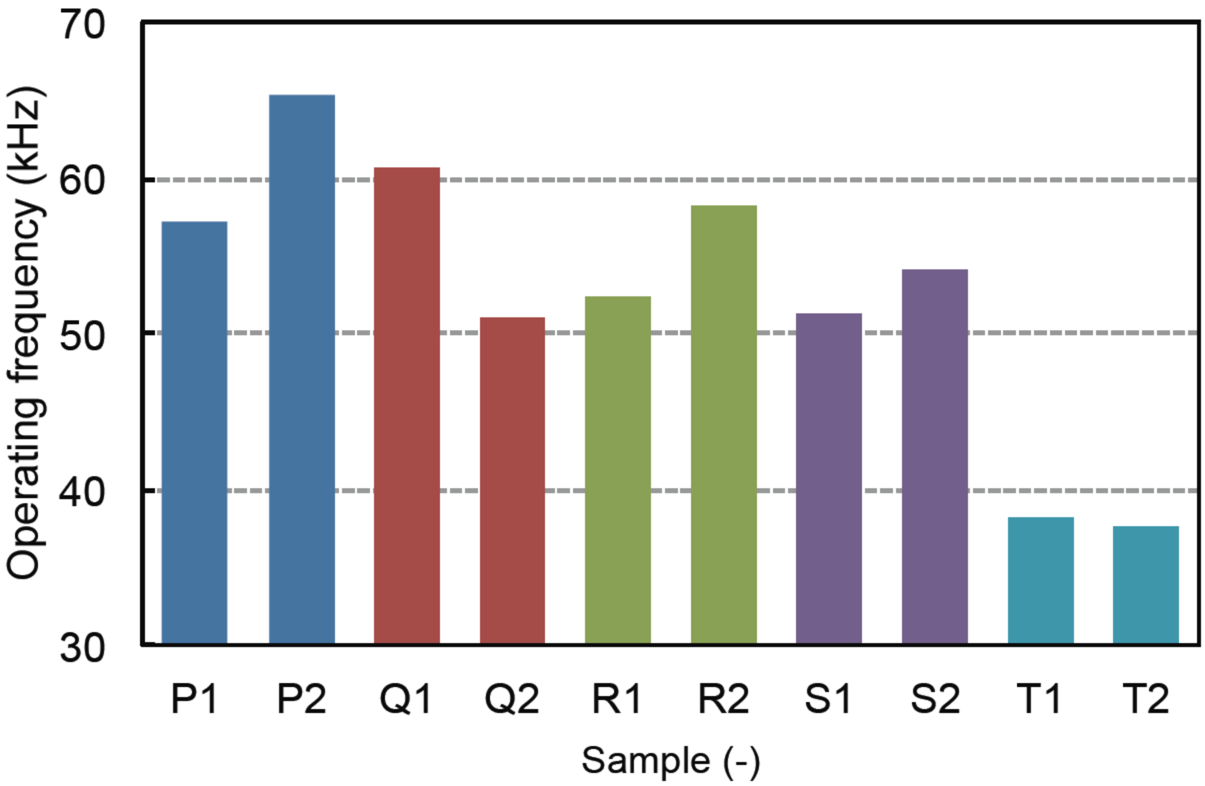


Figure 13: Typical current and voltage waveforms of the lamp circuit, P1.

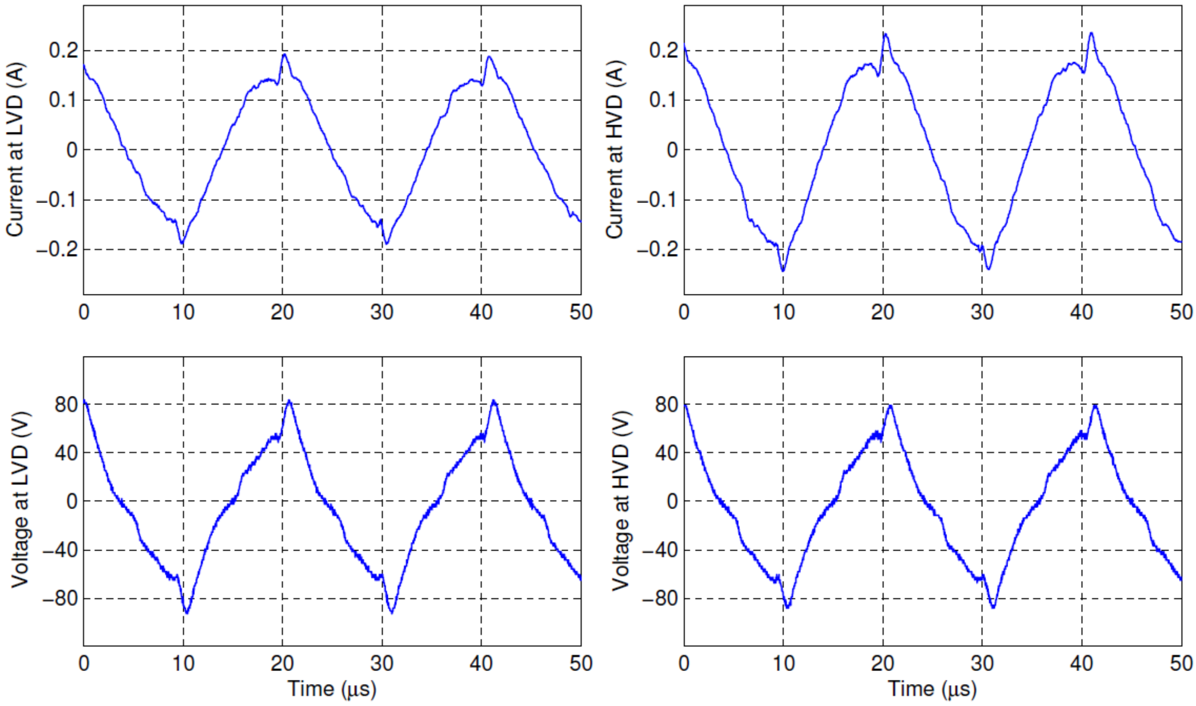


Figure 14: Crest factor of tested lamp circuits at low voltage disconnect (LVD) and high voltage disconnect (HVD).

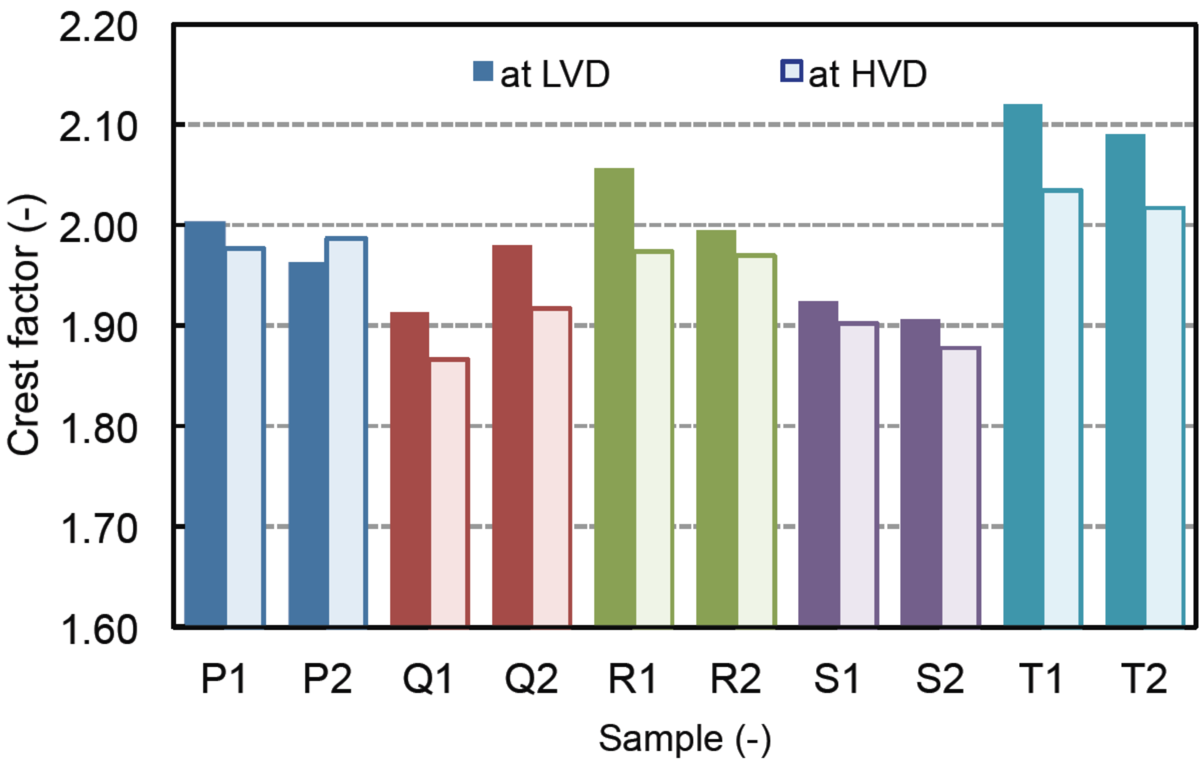
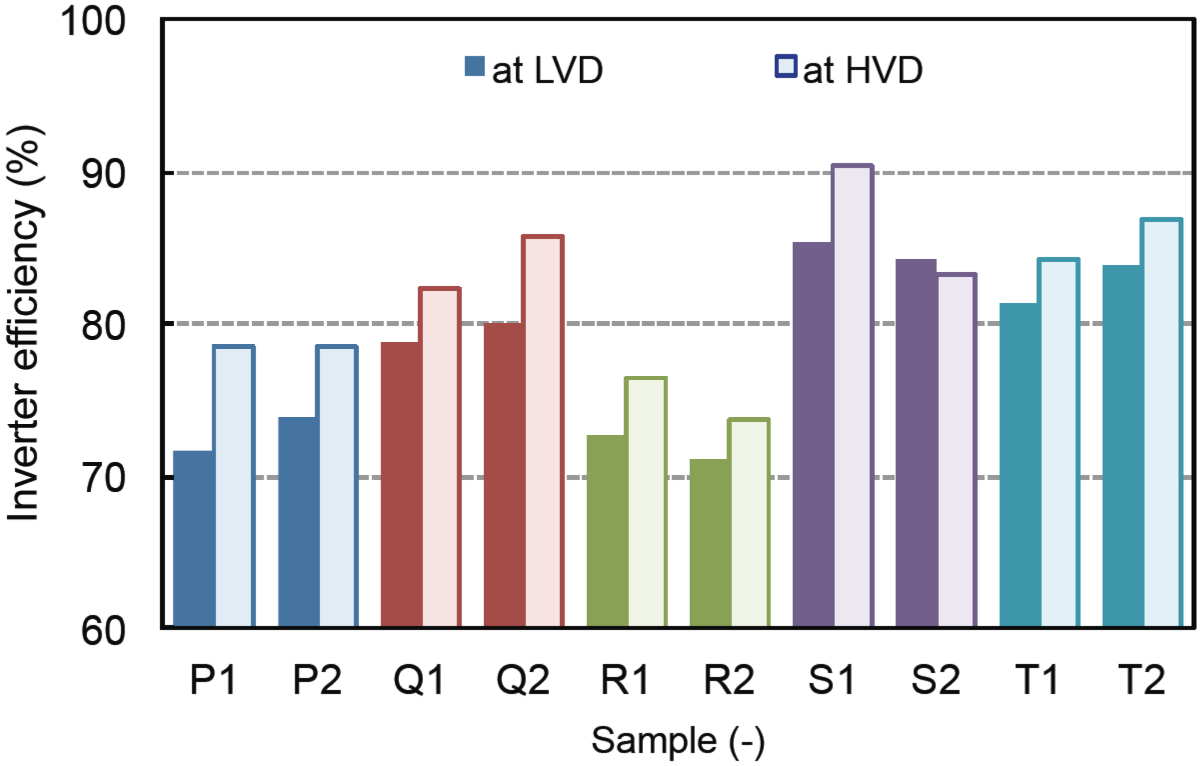


Figure 15: Efficiency of tested lamp circuits at low voltage disconnect (LVD) and high voltage disconnect (HVD).



Tables

Table 1: Tests performed on different SHS components.

Component	**Test item**	**Criteria**	**Level of compliance***
PV panel	Capacity	At least rated	Mandatory
Battery	Capacity	At least rated	Mandatory
	Specific gravity of electrolyte of charged battery	-	-
	Specific gravity of electrolyte of discharged battery	-	-
	Depth of discharge at low voltage disconnect	75%	Mandatory
Charge controller	High voltage disconnect	14:3 0:2 V	Recommended
	Low voltage disconnect	11:6 0:1 V	Recommended
	Self power consumption	<20 mA	Mandatory
	Reverse Polarity Protection	Yes	Mandatory
	Input/output short circuit protection	Yes	Mandatory
	Over current handling capacity	130% of rated current for 1 hr	Mandatory
	Reverse current leakage protection	Yes	Recommended
Lamp circuit (inverter)	Operating voltage	125% of rated voltage	Mandatory
	Efficiency	80% over operating voltage range	Mandatory
	Crest factor	<2	Mandatory
	Operating frequency	>20 kHz	Mandatory
	Reverse polarity protection	Yes	Recommended
	No load protection	Yes	Recommended

*Refers to compliance with the technical specifications for SHS in Bangladesh [23].

Table 2: Statistics on tested PV panels.

Manufacturer	Origin		Rated capacity (Wp) / Count (-)														Total
	Int'l	Local	10	15	20	35	40	50	60	65	74	75	80	85	90	100	
M1	2				2												2
M2	1											1					1
M2	9				2		2	1		2				2			9
M3		4										2	2				4
M4	12	0			2		2	2		2		2		2			12
M5		4					2	2									4
M6	2													2			2
M7	1							1									1
M8	1						1										1
M9	20		2		2	2	2	2	2			2	2	2	2		20
M10		4								2				2			4
M11		2						2									2
M12	2						2										2
M13	2											2					2
M14	10				2		2	2				2		2			10
M15	10				2		2	1		2		2				1	10
M16	8				2		2	2								2	8
M17	2				2												2
M18	14		2	2	2		2			2	1			1	2		14
M19	4				2					2							4
M20	3				2			1									3
M21	6						2	2	2								6
Total	109	14	4	2	22	2	20	19	4	12	1	13	4	13	4	3	123

Table 3: Tested batteries and their rated size.

Manufacturer	Code	Rated capacity (Ah)
	A1	98
	A2	80
A	A3	55
	B1	100
	B2	100
	B3	80
	B4	80
B	B5	55
	C1	100
C	C2	100
	D1	130
	D2	100
D	D3	80

Table 4: Summary of charge controller test results.

Criteria	Manufacturer code / Sample no.																								Total
	G				H				I				J				K				L				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	(24)
Low voltage disconnect	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	16
High voltage disconnect	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	18
Input short circuit protection	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
Output short circuit protection	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	16
Over current handling	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	16
Self power consumption	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	12
Reverse polarity protection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (= 7)	5	5	5	4	3	3	2	3	5	5	5	5	4	4	4	4	6	6	6	6	3	3	3	3	

Note: 1 = criteria met; 0 = criteria not met.

Table 5: Summary of inverter circuit (fluorescent lamp) test results.

Criteria	**Sample**										**Total**
	P1	P2	Q1	Q2	R1	R2	S1	S2	T1	T2	(10)
Operating voltage	1	1	1	1	1	1	1	1	1	1	10
Operating frequency	1	1	1	1	1	1	1	1	1	1	10
No load protection	1	1	1	1	1	1	1	1	1	1	10
Voltage waveform symmetry	1	1	1	1	1	1	1	1	1	1	10
Crest factor	0	1	1	1	0	1	1	1	0	0	6
Reverse polarity protection	1	1	0	0	1	1	0	0	1	1	6
Efficiency	0	0	0	0	0	0	1	1	1	1	4
Total (7)	5	6	5	5	5	6	6	6	6	6	6

1 = criteria met; 0 = criteria not met.