EVALUATING THE QUALITY OF THE LED LAMPS THAT ARE APPROPRIATE FOR USE WITH OFF-GRID SOLAR HOME SYSTEMS (SHS) IN BANGLADESH

By

Asif Hassan

A Thesis Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Environmental Systems: Energy, Technology, and Policy

Committee Membership

Dr. Arne Jacobson, Committee Chair

Dr. Steven Hackett, Committee Member

Dr. Charles Chamberlin, Committee Member

Dr. Rick Zechman, Program Graduate Coordinator

May 2016

ABSTRACT

EVALUATING THE QUALITY OF LED LAMPS THAT ARE APPROPRIATE FOR USE WITH OFF-GRID SOLAR HOME SYSTEMS (SHS) IN BANGLADESH

Asif Hassan

Almost 75% of the rural Bangladeshi-population does not have access to grid electricity. The solar home systems (SHS) program in Bangladesh, which is managed by the Infrastructure Development Company Limited (IDCOL), has provided millions of rural Bangladeshis with access to electric lighting. LED lamps are a key energy efficient appliance used with off-grid SHS. The goal of this research is to collect and analyze data about the quality and performance of LED lamps sold in the Bangladesh market. Fieldwork and laboratory testing using methods specified in IEC Technical Specification 62257-12-1 were used to collect information about the use, sales, quality, and performance of these lamps. The results showed that the IDCOL-approved lamps had higher performance and better durability than the local-market products, although the former products were more expensive. The average prices of the IDCOL-approved and local-market products were Bangladeshi Taka (BDT) 457 ($5.83) and 113 ($1.44), respectively. The average lumen output values for IDCOL-approved and local-market lamps were similar at 259 lm and 247 lm, respectively, but the average luminous efficacy for IDCOL-approved products was much higher, at 83 lm/W, than the corresponding value for the local-market lamps, at 50 lm/W. The IDCOL-approved products also

performed better with regard to durability metrics such as lumen maintenance and workmanship quality. A performance analysis shows that households can receive about 66% more lighting service, measured in lumen hours per day, by using IDCOL-approved LEDs rather than local-market products. This research highlights the importance of laboratory testing to ensure the quality of LED lamps in the Bangladesh SHS market.

ACKNOWLEDGEMENTS

I am forever indebted to Dr. Arne Jacobson for providing me with the opportunity to pursue my Masters in Environmental Systems at Humboldt State University (HSU). At HSU, I could learn new skills, work in different projects, produce a thesis related to the field of my interest, and grow as an individual. I will always be grateful Dr. Jacobson for all his guidance, encouragement, and support. Without the funding and backing provided by Dr. Jacobson, it would not be possible for me to finish my school, thesis, and project within the projected time period. I also owe my deepest gratitude to my thesis committee members, Dr. Steven Hackett and Dr. Charles Chamberlin, for all their guidance and assistance.

I am thankful to the Schatz Energy Research Center (SERC) for providing me the financial support in the form of Schatz Energy Fellowship. Special thanks to Dr. Peter Lehman and Jim Zoellick for their compassion and support. In addition, I would like to thank all the wonderful people from Humboldt and Bangladesh who contributed to my research, including the SERC lighting lab team, IFC Bangladesh office staffs, IDCOL officials, retail shopkeepers, and partner organization officials.

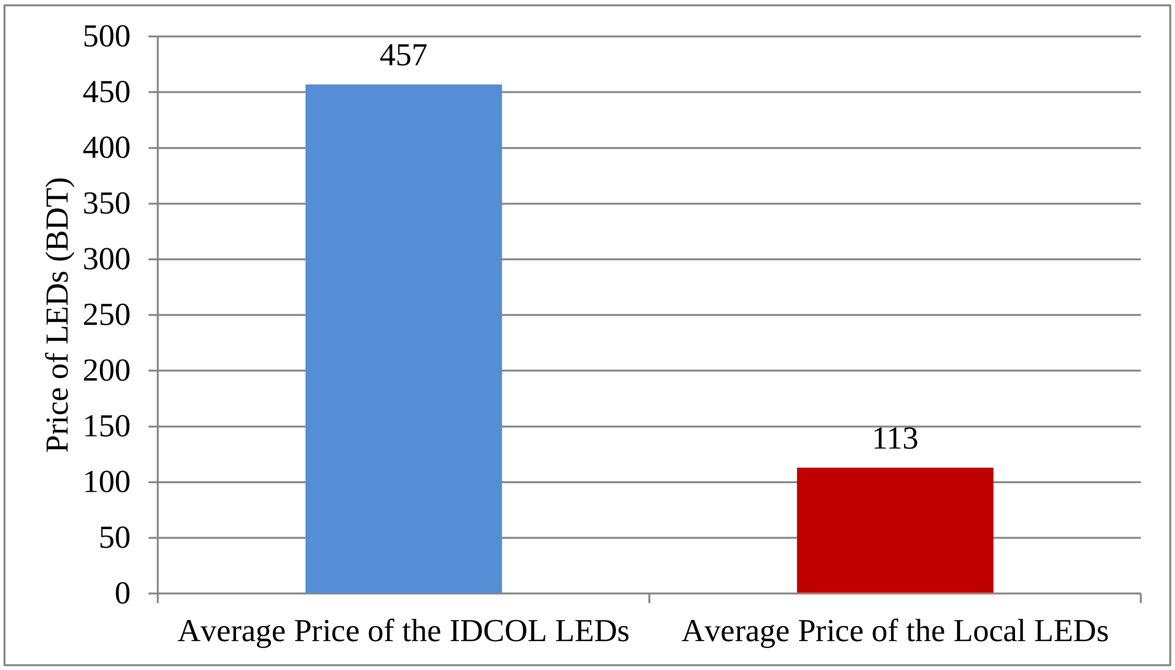
I thank Brendon Mendonca for guiding me during the initial phase of the fieldwork and Jeffrey Mosbacher for assisting me in the laboratory testing. My thesis work would have never touched its level of accomplishment without their support and hard work. I thank Taif Ul Islam, Sadia Haque, Malini Kannan, Janoah Osborne, Kristen Radesky, Mark Rocheleau, Meg Harper, Greg Pfotenhauer, and Mark Severy who all kindly offered their time and thoughts. I would also like to thank Carolyn Ortenburger, Allison Hansberry, and Marc Marshall for offering administrative and technical support during my stay at HSU.

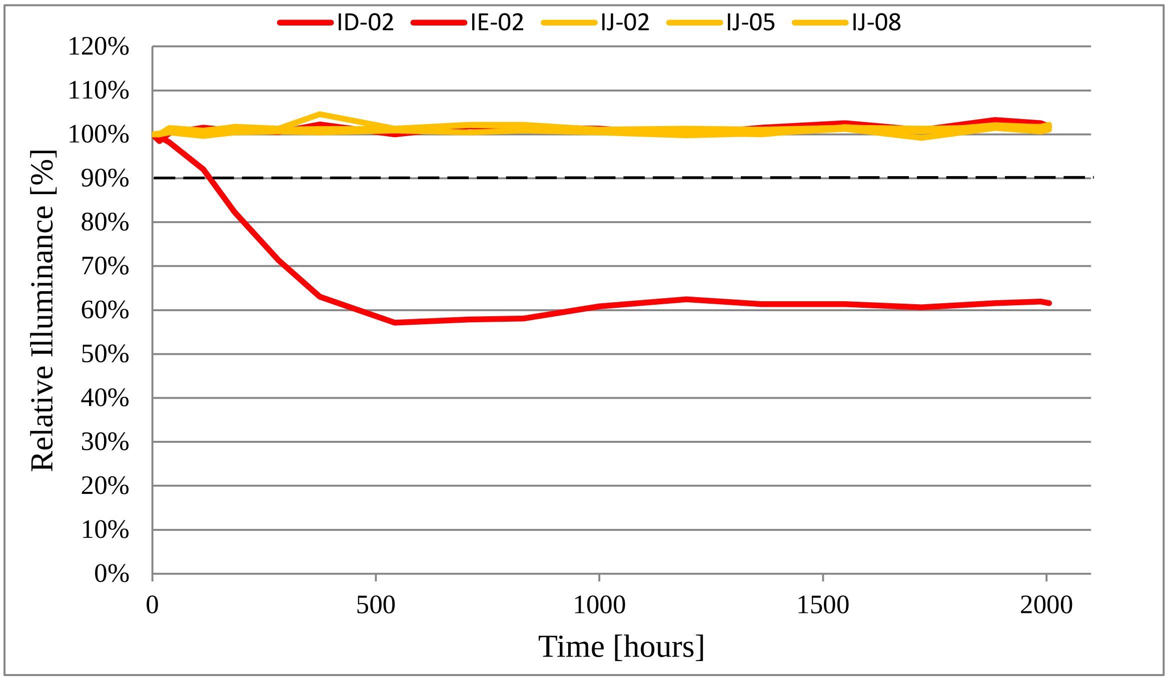
On a personal note, I would like to express my gratitude and love to my ever-supporting family and friends who always believed in me. Their endless love and encouragement made my journey easier. Lastly, I would like to dedicate my thesis to my dad. My dad is my inspiration to achieve all of my goals in life. I love him and miss him a lot.

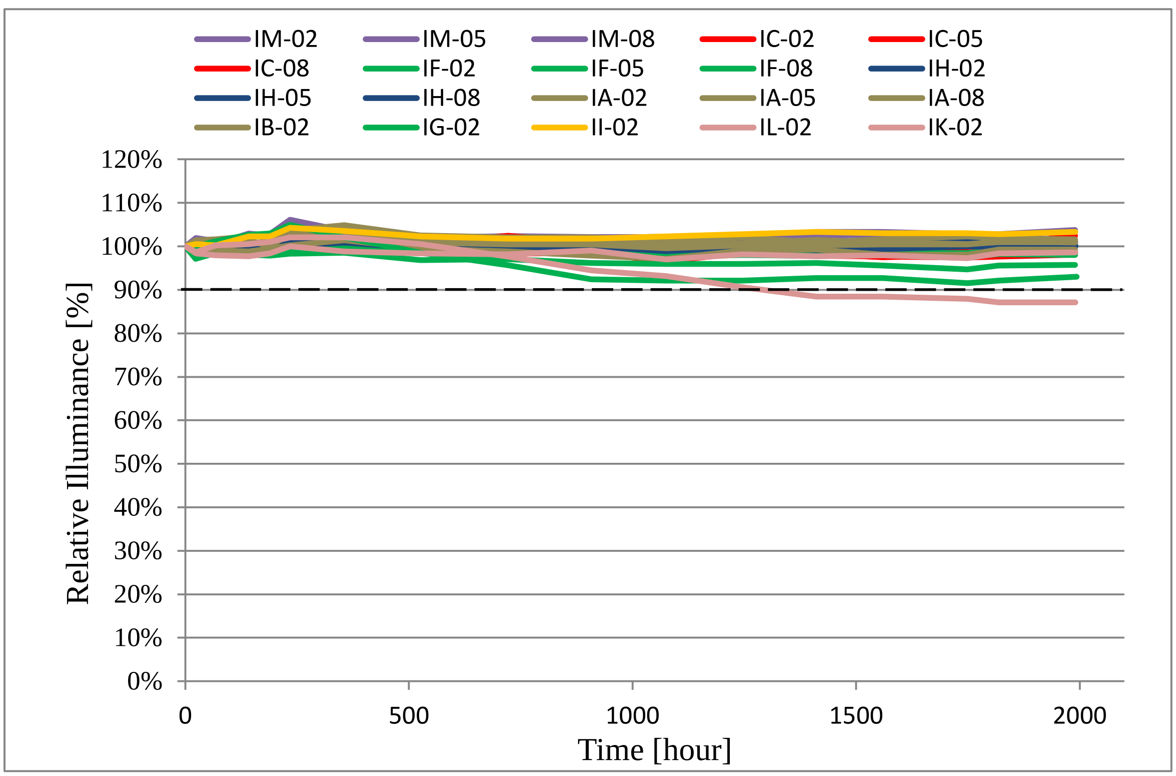
TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES


500
450
400
350
300
250
200
150
100
50
0
Price of LEDs (BDT)
457
113
Average Price of the IDCOL LEDs
Average Price of the Local LEDs


ID-02
IE-02
IJ-02
IJ-05
IJ-08
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Relative Illuminance [%]
0
500
1000
1500
2000
Time [hours]


IM-02
IM-05
IM-08
IC-02
IC-05
IC-08
IF-02
IF-05
IF-08
IH-02
IH-05
IH-08
IA-02
IA-05
IA-08
IB-02
IG-02
II-02
IL-02
IK-02
120%
110%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Relative Illuminance [%]
0
500
1000
1500
2000
Time [hour]

LIST OF APPENDICES

INTRODUCTION

LED lamps are proven technologies that can provide clean and reliable operation when connected with an off-grid solar renewable power system. LED technology is considered as an integral part of energy efficient appliances used with off-grid solar home systems (SHS) in Bangladesh. Bangladesh has the largest off-grid solar market in the world, with over three million systems installed over the past decade (Lighting Global, 2015). This research mainly focuses on LED lamps that are used in the context of the SHS program in Bangladesh managed by the Infrastructure Development Company Limited (IDCOL), a government owned financial institution. IDCOL is implementing a large-scale SHS program in Bangladesh. Although IDCOL's SHS projects are successful, they face some difficulties with the quality of key components, including LED lamps. Therefore, it is very important to evaluate the quality of LED lamps that are used in off-grid SHS in Bangladesh. This research will benefit Bangladesh's solar market as well as other off-grid solar markets around the world.

Objective of the Work

The main objective of this research is to measure the quality and performance of LED lamps that are currently used in the market and to identify opportunities for improvement. To achieve this objective, it is very important to collect data regarding the quality and efficiency of LED lamps that are currently used in the Bangladesh solar market and to analyze these data to determine the main failure modes. At present the LED lamps that are used for the SHS program are approved by IDCOL and included on IDCOL's lists of approved SHS equipment (Siegel & Rahman, 2011). However, it is unclear what test methods are used by IDCOL-sanctioned test facilities to determine if the LED lamps meet IDCOL's requirements. According to IDCOL's requirements the minimum power and luminous efficacy of the LED lamps should be respectively one watt and 80 (lumen/watt). IDCOL expects the lamps to produce at least 80% of their initial light output after three years or 5,000 hours. The color of the light is expected to be white. In addition, POs must provide their customers a three-year warranty period for all LED lamps that they sell to customers (IDCOL, 2016).

This research helps to highlight the importance of rigorous testing according to appropriate and reasonably low cost test methods. At the same time, the results of the testing help determine the quality and performance of the off-grid LED lamps available in the Bangladesh market. LED lamps can be very energy efficient when good-quality, high-efficiency devices are used. However, when poor quality LED lamps are used, the lamps may fail prematurely, thereby undermining confidence in the technology and increasing costs for end-users. The fieldwork element of this research included market evaluation of LED lamps, assessments of market presence for these lamps, surveys of retail vendors and sales agents regarding quality, performance and affordability, and collection of samples of widely used LED lamp models. The process yielded useful data, and it also benefitted participants by increasing their knowledge and awareness about energy efficient appliances and product quality.

In this document, I start by providing a literature review and background information that highlights the importance of the research. This section includes an overview of the Bangladesh SHS market, a summary of quality issues associated with the SHS market, an overview of LED lighting technology, and a discussion about quality issues that are specific to LED lamps. The literature review and background section is followed by a description of the methods used in this study, including data collection methods used in the context of fieldwork and laboratory testing. Next, I present the results of the study, which include survey results, laboratory test results, and other findings. This section is followed by a discussion and recommendation section, which covers my main findings, highlights the importance of laboratory testing, and indicates promising approaches for action. These approaches could be used to help to overcome key problems related to LED lamps used in Bangladesh market. In the conclusion, I explain how the results from this research are useful for interested parties, including product manufacturers, distributors, partner organizations, IDCOL officials, and other policy makers. I also mention how LED lamps play a vital role for the growth of SHS market in Bangladesh. This research can contribute to efforts to ensure the quality of LED lamps not only in Bangladesh market, but also in other off-grid markets where solar systems and related technologies are used.

LITERATURE REVIEW AND BACKGROUND

Bangladesh has a population of 161 million, with a population density of 1,238 people per kilo meter square. In Bangladesh, only 55% of the population has access to electricity, and the country has been facing severe power crisis for a long time (Sadeque, et al., 2014). The peak demand is 8,500 MW, but the installed generation capacity is about 6,500 MW (Khandker, et al., 2014). The electrification rate in the urban areas is 90%, but only 43% in the rural areas of the country, where majority of the population live. Therefore, there are widespread power outages. Insufficient generation capacity, weak government structure of power sector entities, and limited technical capacity are the key problems associated with the power section of Bangladesh (Sadeque, et al., 2014). Solar energy is the most readily available and free source of energy in Bangladesh (Siegel & Rahman, 2011). Therefore, promoting solar energy along with energy efficient appliances could be a feasible solution to help address the energy crisis of Bangladesh.

In Bangladesh, close to three-fifths of the rural-households do not have access to electricity (Khandker, et al., 2014). Solar home systems (SHS) have provided millions of rural people in off-grid areas with access to electric lighting. In the Bangladesh solar market, SHS installations are mainly driven by the Infrastructure Development Company Limited (IDCOL). IDCOL is a government owned infrastructure financing company, and it controls much of the Bangladesh solar market (Khandker, et al., 2014). The organization receives technical and financial support from international organizations including the World Bank, Asian Development Bank (ADB), and International Finance

Corporation (IFC) (Marro & Bertsch, 2015). In spite of that, no more than ten percent of rural people in off-grid areas have been reached by IDCOL (Khandker, et al., 2014). This means, there is plentiful opportunity for continuous SHS growth in off-grid areas of Bangladesh (Siegel & Rahman, 2011). For the Bangladesh solar market, SHS are considered to be one of the cost efficient solutions for residential electricity delivery where grid supply is still not available. Even so, only a modest fraction of the un-electrified population is wealthy enough to afford a SHS. A number of nongovernmental organizations (NGOs) are working with IDCOL to make the SHS program a success. The NGOs are known as partner organizations (POs), and they are the main distributors of SHS in the Bangladesh solar market (Khandker, et al., 2014). The partner organizations (POs) have to get the approval from IDCOL before they start their business (Islam, 2014). The main tasks of the POs are to select project regions and prospective customers, extend loans, install the systems and offer maintenance support (Khandker, et al., 2014).

All SHS components sold by POs must be approved by IDCOL, including the LED lamps (Siegel & Rahman, 2011). But there is also a big local SHS market present in Bangladesh that is separate from IDCOL. The local vendors are also equipped to install SHS in households, and they sell all the relevant solar equipment and appliances. They also charge their customers less money for the systems than the partner organizations do. In addition, these vendors provide support to their customers, including installation and after sales service support. These local vendors are affecting IDCOL’s command over the solar market in Bangladesh. The local vendors also supply customers with LEDs and at a cheaper price. There are numerous shopkeepers or retailers who sell LEDs in the local market in Bangladesh. Most of the LEDs are imported from China, and the lamps are assembled locally. There are concerns about the quality of these local-market LED lamps. This is a known issue in the Bangladesh solar market. But due to the low price of the LEDs many of customers choose to purchase the lamps from the local market. The purpose of this research effort is to determine the difference in quality between the IDCOL-approved LEDs and local-market lamps.

History and Evolution

IDCOL started its solar energy program in January 2003. The initial installation target was 50,000 solar home systems (SHS) in off-grid areas within five and half years (Khandker, et al., 2014). This target was achieved in August 2005, three years ahead of the target date and two million US dollars below the estimated cost. Following IDCOL's success, the International Development Association (IDA), German Federal Enterprise of International Cooperation (GIZ), German Development Cooperation (KfW), Asian Development Bank (ADB), and Islamic Development Bank (IDB) extended support for the program. IDCOL revised its target to one million SHS by 2012. Then IDCOL revised its target to six million SHS by 2016 (Islam, 2014). Table 1 represents the year wise installation rate of IDCOL solar home systems.

Table 1. Year wise SHS installation rate by IDCOL (Haque, 2016).

Year	Number of SHS Installed
2003	11,697
2004	20,635
2005	27,579
2006	37,151
2007	69,562
2008	103,301
2009	169,916
2010	324,775
2011	469,572
2012	643,812
2013	750,483
2014	724,615
2015	451,623

In addition to refinancing, IDCOL also provided grants to lower costs of SHS and build institutional capacity of the partner organizations (Siegel & Rahman, 2011). IDCOL's principal objective is the commercialization of SHS. Therefore, IDCOL has adopted a policy of reducing the size of the grants over time according to the progress of the project. IDCOL's SHS program has the mission of fulfilling basic electricity requirements in the rural areas of Bangladesh, thereby supplementing the government's vision of electrifying the whole of Bangladesh by 2020. The buy-down grant amount is currently US$20 equivalent in Bangladeshi Taka (BDT) per system (Siegel & Rahman, 2011). The households buy the systems from the PO branch offices. When they make the purchase, they have to pay ten percent of the total system price as down-payment (Islam, 2014). Sales tax and value added tax (VAT) amounts are included within the system price. POs offer loans to the households. The loan tenure varies from one to five years.

The interest rate varies from eight percent to fifteen percent per annum based on different conditions, and repayment frequency is monthly (Karim, 2015). IDCOL also offers refinance amounts to the PO’s. The refinance amount is 70% to 80% of the amount that the PO provided to the households (Khandker, et al., 2014). The loan tenure, including a grace period, varies from five to seven years, and the interest rate varies from six percent to nine percent per annum based on different conditions (IDCOL, 2014b).

The year wise increasing installation rate of the SHS panels is the evidence of the success of this program, which has been shown in Figure 1. But IDCOL experienced a significant drop in the sales in 2015. This suggests that IDCOL’s SHS business may be facing some difficulties. IDCOL, with support from the International Development Association (IDA) and Global Environmental Facility (GEF), is channeling both grant funding and refinanced loans to renewable energy projects in rural areas under this program. Qualifying POs, such as NGOs and private sector companies, can apply for financial help and refinancing from IDCOL. The finance for the IDCOL SHS program mainly comes from donors such as the World Bank. IDCOL provides loans and grants to the partner organizations (Lighting Global, 2015). The POs then recognize customers, install the SHS, and deliver after-sales support to the customers (IDCOL, 2014a). The program structure is illustrated in Figure 2, below.

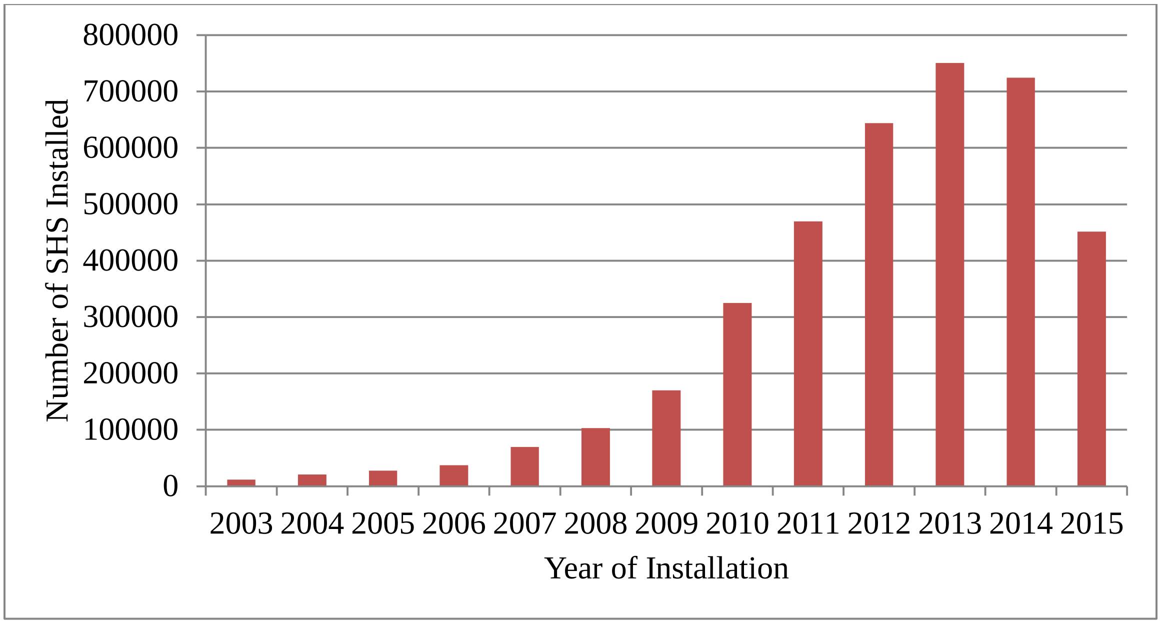


Figure 1. Year wise SHS installation rate by IDCOL (Haque, 2016).

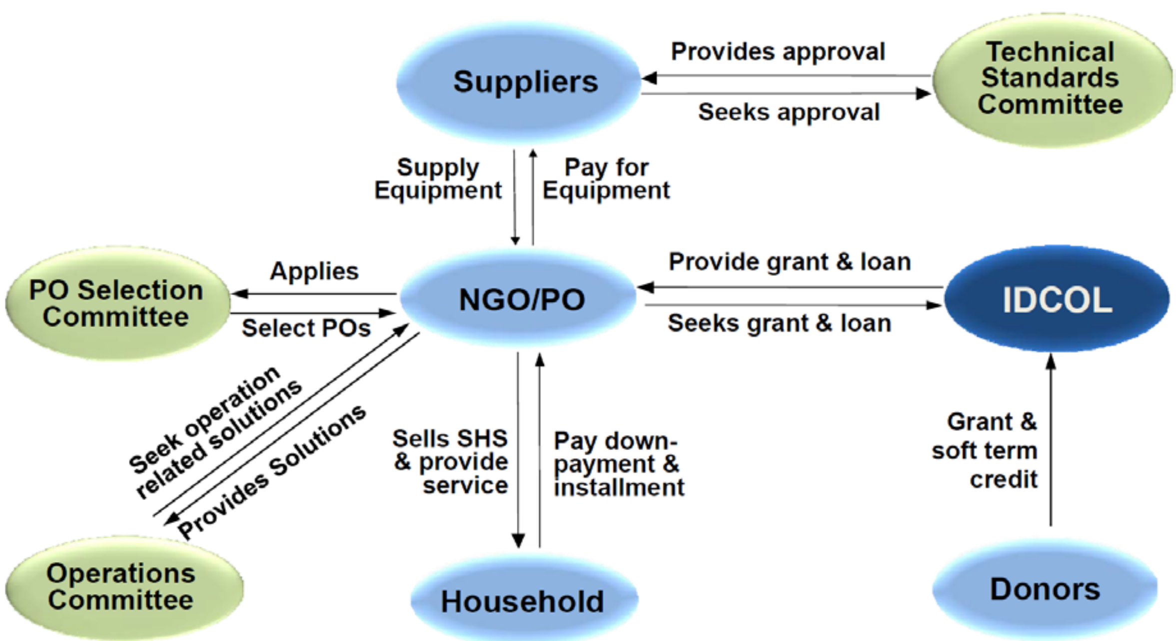


Figure 2. IDCOL solar home systems (SHS) program structure (Islam, 2014).

Success and Challenges

IDCOL has invested about 560 million US dollars so far (Islam, 2014), and it had installed 3.8 million SHS as of January 2015 (Haque, 2016). Figure 1 represents the rapid growth of IDCOL's SHS installations from 2003 to 2013. But after 2013 the graph indicates a steep decline in the number of SHS installations. IDCOL aims to invest a cumulative total of one billion dollars by the end of 2016 and aims to finance six million SHS by 2017 (Lighting Global, 2015). Given the recent decline in sales, it is unclear if IDCOL will meet these targets. Figure 3 shows the approximate geographic distribution of SHS installations by division. The figure indicates that the distribution of the SHS is highest in the Dhaka Division and lowest in the Rangpur Division.

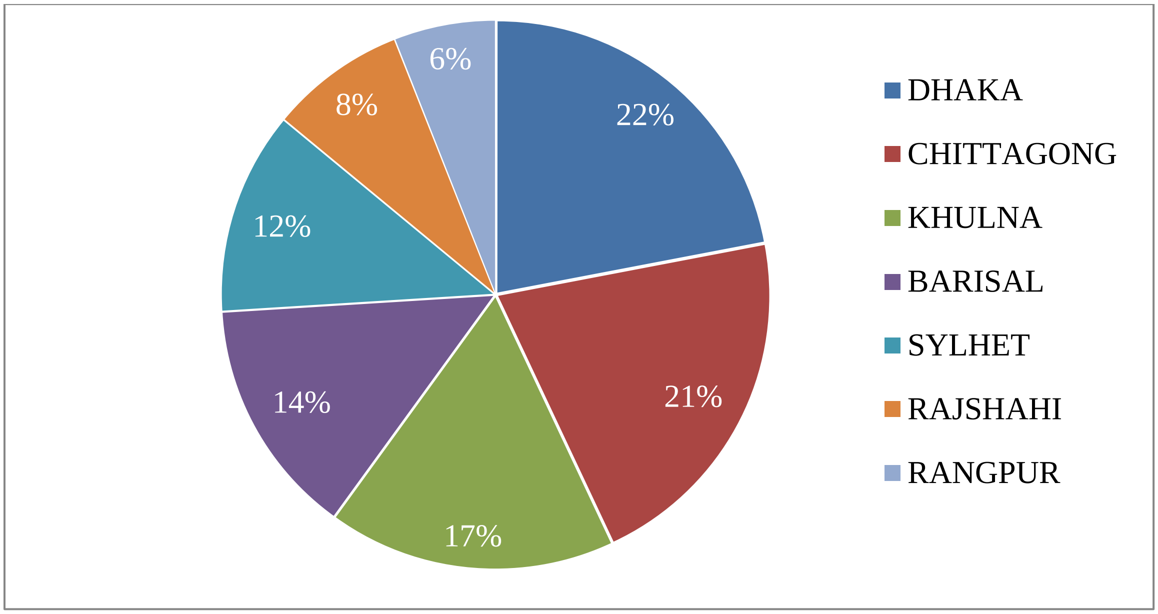


Figure 3. Distribution of the IDCOL SHS in seven divisions in Bangladesh (Haque, 2016).

Although there has been considerable success in the renewable energy sector in Bangladesh, there have been plenty of obstacles to overcome. Unavailability of information about the feasibility of the technology discourages investors from developing a bigger plan of action. Bangladesh currently does not have central database that includes information that would facilitate implementation of pre-feasibility studies by potential project developers. In addition, the current set of environmental laws and acts of the country do not match contemporary policy goals, as they were brought into force quite a long time ago (Zobaer, et al., 2013). The high installation cost of solar technology is probably a key barrier for switching towards renewable energy sources (Siegel & Rahman, 2011). Local capacity for project development and system design, installation, operation and maintenance is also very limited (Zobaer, et al., 2013). Moreover, the distribution rate of the SHS in the various divisions of Bangladesh is not uniform (Haque, 2016).

In addition, the reputation of the SHS components, including solar PV panels, batteries, and LED lamps, has a huge impact on the solar market. Word of mouth communication is the key to establish the positive reputation of SHS technology in the rural areas of Bangladesh. In fact, to stimulate sales of SHS, word of mouth may play a more important role than subsidies that reduce system cost (Siegel & Rahman, 2011). In rural areas, most people have limited access to and understanding of advanced technologies, and almost none have access to information via internet and computer. Therefore, word of mouth plays a vital role in the advancement or disruption of IDCOL's development of off-grid solar in rural Bangladesh. In urban areas, it is easier for people to verify the quality of the SHS components by themselves due to easy access to modern technology. They can verify and form their own understanding using internet and computer resources, for example. Thus, the impact of negative advertising is higher in rural areas compared to urban areas. Solar home systems are more common in rural areas of Bangladesh than in urban areas. Most of the POs have their branch offices in rural areas where off-grid power is the only source of electricity. LED lamps are sold to customers along with the SHS. In rural areas the majority of the people are not educated enough to verify and compare the quality of the products by themselves, and they therefore often rely on other's opinions. For these people, the effect of word of mouth is enlarged if an opinion leader or another influential person conveys it (Siegel & Rahman, 2011).

The customers living in the rural areas do not have detailed technical knowledge about SHS components. This knowledge gap creates uncertainty in the minds of the customers about the worth and reliability of the components. This is one of the main reasons for market spoiling which eventually causes market failure. The majority of the SHS owners are ignorant of the brand of the panel modules, batteries, controllers, and LEDs. They may suffer major financial losses by purchasing the wrong brand of the SHS components and lose confidence in the SHS components, which can lead to market failure (Duke, et al., 2002). The concept of information market failure was first discussed by George Akerlof. In his classic paper, Akerlof explained the reasons of the market failure due to inadequate information and introduced the concept called the “market for lemons” (Akerlof, 1970). There are plenty of different brands of LED lamps available in the Bangladesh solar market. Unfortunately, the majority of the customers do not have access to adequate information about the quality and performance of these lamps. Therefore, by purchasing low-quality brands of LEDs, customers easily lose confidence in the LED technology. In general, the distributors and shopkeepers are more informed about the quality of their products than the customers. Even so, they do not have the highest level of technical knowledge about the product quality. Customers uncertainty about product quality may constrain sales of all types of SHS. This, in turn, could hurt the overall growth of the SHS market (Duke, et al., 2002). As a result, financial agencies that might otherwise support adoption of energy efficient appliances by providing financing services for SHS could be less likely to invest in and offer financial services in communities where market spoiling has occurred. This market spoiling effect can exist in any market that involves information assymetry and a mix of good and poor quality products. An example of the market spoiling effect related to LED products in Kenya is discussed in a paper written by Alstone and colleagues (Alstone, et al., 2014).

Role of Efficient Appliances

To fulfill the government's vision within the time limit, it is very important for IDCOL to ensure the quality of the energy efficient appliances that are included in the SHS that it supports. Therefore, IDCOL has been financing several energy efficient projects (IDCOL, 2014c). Promoting LED lamps and lanterns in the place of compact fluorescent lamps can be a key point of emphasis. LED lamps are generally more efficient than compact fluorescent lamps (CFLs). CFL lights have adverse effect on human health (NEWAGE, 2014). The average life span of the LED lamps is longer than CFLs, and, in most cases, less electricity is used by LEDs to produce an equivalent amount of light (U.S. Department of Energy, n.d.). CFLs also contain toxic mercury which contaminates the environment, while LEDs do not have a significant negative impact on the environment. It is possible to reduce energy consumption by replacing fluorescent lamps with LED lamps (Scoyk, 2010).

However, in the Bangladesh's solar market the initial price of the LED lamps is higher than the price of similarly sized compact fluorescent lamps (CFLs). In Bangladesh, almost 75% of the total population lives in the rural areas (UNICEF, n.d.). To convince the majority of the consumers to use the LED lamps instead of CFLs is a challenging task, especially in a country like Bangladesh where 36% of the rural population lives under the poverty line (Rural Poverty Portal, 2012). But given the recent decline in prices and increase in efficiency of LED lamps, there is growing interest to adopt LED technology widely for use in SHS in place of the incumbent technology, CFLs. In fact, the Bangladeshi government has decided to shift its focus on LEDs from CFLs to reduce overall energy consumption (NEWAGE, 2014). However, early adoption of LED lamps has had mixed success, as some of the products have not performed as advertised. In practice, LEDs represent an improvement only if their quality and performance actually do exceed those for CFLs. All these key factors along with the better quality of light, performance, and longer durability can motivate the desired transition to LED lamps. The importance of efficient appliances is discussed in a paper written by Phadke and colleagues (Phadke, et al., 2015).

Quality Issues in Bangladesh Market

The source of information for this particular section is my field work observations. LED lamps currently available in the Bangladesh solar market vary in quality, and most consumers do not have any access to information or finance to help them select and purchase better quality lamps. Firstly, consumers need assurance that these lamps will fulfill their lighting needs. Secondly, these lamps generally have a longer life span than CFLs. These two points could help to convince consumers to choose LED lamps over CFLs. This part of the research is particularly important because of the market spoiling phenomenon, in which consumers are turned away from new lighting technologies based on their previous negative experiences with low quality lighting appliances.

Maintaining high quality of off-grid products is very important for the Bangladesh solar market. One of the main goals for this is to help partner organizations make informed purchasing, investment, and regulatory decisions and to ensure that the systems delivered to end-users operate effectively and as advertised. Different policy tools (e.g. product quality standards, warranty requirements, etc.) can be used to achieve these goals. IDCOL must ensure that its requirements have been met by the distributors and suppliers. LED lamps are an integral part of the SHS business and must meet all the requirements set by IDCOL's technical standards committee (IDCOL, 2016). A majority of customers buy LEDs from the local market. For this reason, it is very important to validate the quality of LEDs sold in the local market. IDCOL plays a key role in maintaining standards for LEDs sold by the partner organizations. Unfortunately, at present there is no quality assurance program available to maintain the quality of the local- market LEDs.

The price of the LEDs available in the local-market is lower than the LEDs sold by the partner organizations. The average price of the local-market LED lamps was BDT 113 ($1.44), which was considerably lower than the average price for IDCOL-approved lamps, BDT 457 ($5.83). Local-market vendors do not receive any financial support from the government or other organizations. They only rely on their personal capital or bank loans to manage their business. By compromising on product quality, local vendors are able to sell their products at a lower price and make profit. For this reason, local vendors or retailers of LEDs may be less concerned about maintaining the quality of their products than the IDCOL POs. This situation can be changed by providing benefits to those that meet quality requirements and by enforcing a reasonable set of consequences for those that do not. In this research, two different methodologies were used to collect information about LED lamps in the Bangladesh market. First, a well-organized protocol was followed for data collection during a fieldwork phase. Fieldwork methods consisted of a LED lamp vendor survey, interviews, and other related data collection. This made it possible to gather information about LED lamps and testing facilities available in Bangladesh. During the fieldwork phase I also collected LED lamp samples from PO branches and local-market vendors. Second, laboratory testing was used to measure the quality and performance of the collected LED lamps. The lab testing was based on the methods described in International Electrotechnical Commission (IEC) Technical Specification 62257-12-1 (IEC, 2015). The test results made it possible to identify opportunities for improvement.

LED Lighting Technology

The term LED stands for light emitting diode (NEWAGE, 2014). LEDs are semiconductor devices. When an electric current or field passes through the LEDs they produce visible light. In general, high-quality LED lighting products are very efficient (U.S. Department of Energy, n.d.). But there are also some that are not very efficient. In this thesis work, I will only discuss LED lamps. But in general, LEDs are used for a variety of applications such as indicator lights on electronic devices, LED lamps, flashlights, traffic lights, display boards, home lighting applications, and others. The size of LEDs is very small, which is really convenient from a design point of view. Most LEDs are unidirectional, meaning that they emit light in a particular direction (U.S. Department of Energy, n.d.). It is important to consider the unidirectional nature of LEDs when designing lamps. This ensures an appropriate distribution of light output of the lamps for any given application. Importantly, some LEDs produce a narrow beam of light, while others have a wide angle design. Incandescent and compact fluorescent bulbs emit light in all directions. Incandescent lights release the majority of the energy as heat. This makes incandescent lighting technology very inefficient (U.S. Department of Energy, n.d.). CFLs are generally more efficient than incandescent lamps, but they do still generate a fair amount of heat (Haldman, et al., 2008).

LED lighting technology have many advantages (e.g. long lasting, energy efficient, environment-friendly, low voltage requirement, brightness, low power consumption, flexible design, zero UV radiation, etc.). In addition, when they are designed properly, the heat produced by the LEDs is absorbed into a heat sink. This controls the temperature and helps ensure the longevity of LEDs (U.S. Department of Energy, n.d.). Although LEDs have a lot of advantages, they also have some disadvantages such as voltage sensitivity, temperature dependence, and high price. Voltage sensitivity refers to the minimum change in the voltage level that yields a noticeable change in the output of the lamps (LEDKE Technology, 2010). The supplied voltage should be kept above the threshold to avoid this issue. In addition, the supplied current should be kept below the rating. High ambient temperature causes overheating, which leads to failure of the LEDs. The use of heat sinks can prevent this overheating. LED lamps are more expensive than most of the other lighting technologies. Use of high brightness LEDs minimizes the number of LEDs used per lamp, thus making LED lamps competitive with other lighting technologies (Luminanz Ltd, 2011). But with time LED lighting technology will become even more advanced and amazing.

LED lights come in different colors, including red, blue, white, green, and amber. There are two main ways of generating white LED light. The use of a phosphor is the more common way of generating white light using an LED, but some products generate white light by mixing colors (Haldeman, et al., 2008). In the Bangladeshi solar market there are different types of LEDs available. The quality varies based on the brand and price of the LED lights. LEDs purchased from the local LED market did overheat more during use than the IDCOL-approved ones. Lack of a proper heat sink could be one of the potential reasons for that. To avoid overheating, the heat produced by the LEDs must be drawn away from the LEDs. For this reason, heat sinks are crucial to achieve high performance over an extended time period with LED lighting technology. This passive device absorbs the heat and dissipates it into the environment. LEDs are very sensitive to temperature, and their lifetime is shortened if they operate at a temperature that is too high (LEDKE Technology, 2010). The methods for lumen maintenance testing for LEDs are described in International Electrotechnical Commission (IEC) Technical Specification 62257-12-1 (IEC, 2015).

Quality Issues of LED Lights

The LEDs sold by the POs must meet requirements set by IDCOL. If the POs fail to fulfill these requirements, they are at risk of losing support from IDCOL (IDCOL, 2016). Some of the leading POs have their own testing facilities for LEDs. However, these facilities are only capable of conducting a few basic tests, and they do not allow for a comprehensive evaluation of LED lamp quality and durability. Many companies import complete products from China, while others assemble lamps locally using imported components. The partner organizations or distributors for LEDs each have their own affiliation with the various local and Chinese manufacturers. For this reason, it is the responsibility of the POs to let their suppliers know about IDCOL's quality requirements for LED lights. Before importing the LEDs from China, most of the POs make sure that the quality requirements of the LEDs have been fulfilled by the manufacturers. At present, few local authorized testing institutions in Bangladesh have the capability to carry out testing of LEDs (IDCOL, n.d.). The minimum warranty period for the LEDs sold by the POs is three years (IDCOL, 2016). This strong warranty requirement requires the POs to be serious about the quality of the lamps that they sell. Most of the local vendors do not offer any warranty for their products. But a few retailers offer a warranty period of one to two years for their LED products. The retailers that do offer a warranty typically replace the defective LEDs with new ones. However, they typically use the term guarantee rather than warranty in their communications with their customers. The price of LEDs with a guarantee period is higher than the price for ones without a guarantee.

Upon request by their customers, some market vendors can provide LEDs with a guarantee.

Given the variations in LED lamp performance and the fact that most buyers do not currently have access to information about product quality to help them select and purchase better quality lamps, a study focused on measuring and reporting the quality and performance of the LED lamps is beneficial. This study therefore focuses on measuring the quality and performance of the most widely used LED products in the Bangladesh SHS market. In the context of the study, I collected information from LED product vendors to learn about their experiences with the products. The information collected in the study will help inform Bangladesh policy makers about the extent of quality issues with LED lamps. It will also demonstrate that low cost test methods that could be adopted by Bangladesh test labs can be used to carry out LED lamp testing. If widely and consistently implemented, these methods could be used to address LED lamp quality problems in the Bangladesh SHS market.

METHODS

The method section for this research is categorized into two segments: fieldwork and laboratory testing. Fieldwork was completed to identify the most common brands of LED lamps in the Bangladesh solar market. Based on data collected during the fieldwork portion of the study, lamps were purchased from the Bangladesh off-grid solar market. Second, the lamps were then tested in the laboratory of the Schatz Energy Research Center, Arcata, California. To determine possibilities for improving the quality of the LED lamps in Bangladesh, it was essential to establish an understanding of the current situation with regard to quality and performance. Each product was evaluated with regard to eight different metrics: light output (luminous flux), lumen efficacy, light color characteristics, light distribution, lumen maintenance, workmanship (based on visual screening), warranty terms, and truth-in-advertising with regard to key performance metrics. A summary of the methods used in the fieldwork and laboratory testing is provided in the following sections.

Methods for Fieldwork and Selecting Lamps

The data collected during the fieldwork portion of the study were the key for selection of the LED lamps. I collected data about LED lamp sales and availability in the market. I used these results along with information about the SHS system sales for the various POs to identify which lamp brands and product models to collect for testing. My goal was to select commonly available lamps from a variety of POs and market vendors in order to obtain a sample that represented a cross section of the LED lamp products that are in use. The fieldwork for this research was performed during June and July of 2015. The methods used in this fieldwork were similar to those used in previous field-studies conducted under the Lighting Asia and Lighting Africa programs. The main field method used was a survey interview involving responses from PO sales representatives and shopkeepers that sold LED lamps. The survey forms are available in Appendix A and Appendix B, respectively. The surveys were conducted in selected sites in four different divisions of Bangladesh including Dhaka, Chittagong, Rajshahi, and Sylhet. Representatives from the Lighting Asia Bangladesh program provided support for the survey effort in the form of information and introductions to key contacts. The Lighting Asia Bangladesh program is an initiative of the International Finance Corporation (IFC). Lighting Asia program staff work closely with the IDCOL program and have detailed knowledge of key SHS market actors in Bangladesh. They were therefore well positioned to help me identify potential candidates for survey interviews. The IFC Lighting Asia staff members also helped with selection of project sites, interview participants, and introduction of key IDCOL officials. The interviews were conducted with a selected sample of adult participants who were retailer shopkeepers and PO sales representatives. The field methods associated with this work were reviewed through Humboldt State University's Institution Review Board (IRB) process (IRB 15-094) and were determined to be exempt from further review.

Category and Context of the Survey

The main objective of interviewing representatives from the two different groups (i.e. PO sales representatives and shopkeepers) was to compare the quality of IDCOL-approved and local-market LED lamps. The survey results provided an understanding of the types of LED lamps available to buyers in both rural and urban areas. Surveys were administered to two groups of people, PO sales representatives and shopkeepers that sold LED lamps that were compatible with use with 12 volt DC energy systems such as a SHS. In the month of June 2015, with support from Brendon Mendonca from the Lighting Asia team in India, I administered six surveys with PO sales representatives and three surveys with shopkeepers (Figures 4 and 5). I conducted the rest of the surveys by myself. I administered the surveys in Bengali and translated the responses into English.

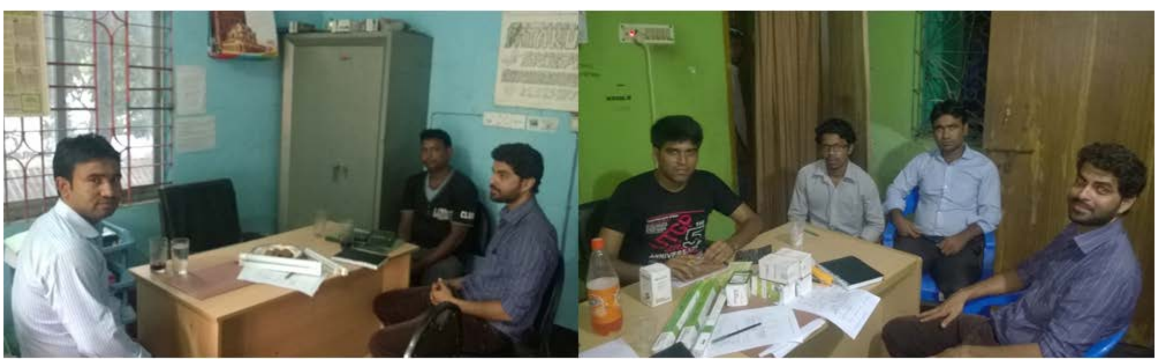


Figure 4. Brendon Mendonca (right in both figures) with PO sales representatives. The photo on the left is the Patakuri branch office in B.Baria (Photo credit: Asif Hassan), and the photo on the right is the Rural Services Foundation (RSF) branch office in B. Baria (Photo credit: Asif Hassan).

PO sales representative surveys were distributed among four different divisions in Bangladesh. The survey questionnaire collected information about 1) the main factors that customers consider when purchasing a lamp (e.g. price, durability, brightness, warranty), 2) the main problems or quality issues that customers have experienced and communicated to the respective sales people (e.g. LEDs become dim, LEDs fail to operate, LEDs break after being dropped), 3) any credit or guarantees/warranties that are offered for the products, 4) details about the LED lighting products that are offered (e.g. brand names, model numbers, power ratings), and 5) estimated sales of the LED products. Information was also collected about the PO (e.g. business name, business location, and the number of employees at the branch). It was also important to gather information about the PO branch office location, total area covered by the branch, and the name and contact details of the interviewee for authentication of the data. This information enabled an analysis of the PO business model that includes the types of products sold and the volume of sales for LED lamps, in the Bangladesh solar market.

Figure 5. Asif Hassan conducting survey with PO sales representatives. On the left is the Integrated Development Foundation (IDF) branch office in B.Baria (Photo credit: Brendon Mendonca) and on the right is the Bright Green Energy Foundation (BGEF) branch office in B. Baria (Photo credit: Brendon Mendonca).

As noted previously, surveys were conducted in four divisions of Bangladesh: Dhaka, Chittagong, Rajshahi, and Sylhet. Representatives of POs were surveyed in each of these four divisions, while shopkeeper surveys were surveyed in three. No shopkeepers were surveyed in the division of Chittagong. The shopkeeper survey form was identical to the PO sales representative survey form. In addition, information about the shop type, the number of employees, and the method of selling (e.g. retail, wholesale, or both) was collected from the shopkeeper survey. The data collected during the shopkeeper survey also enabled an analysis of business activity in the respective local LED markets. Overall, 17 PO sales representatives (two in Dhaka, six in Chittagong, five in Rajshahi, and four in Sylhet) surveys were conducted (Figure 6), and 34 shopkeeper representative surveys (sixteen in Dhaka, eight in Rajshahi, and ten in Sylhet) were conducted (Figure 7). In each case, PO sales representatives were informed about the interviews in advance by a representative from the head office of the respective PO.

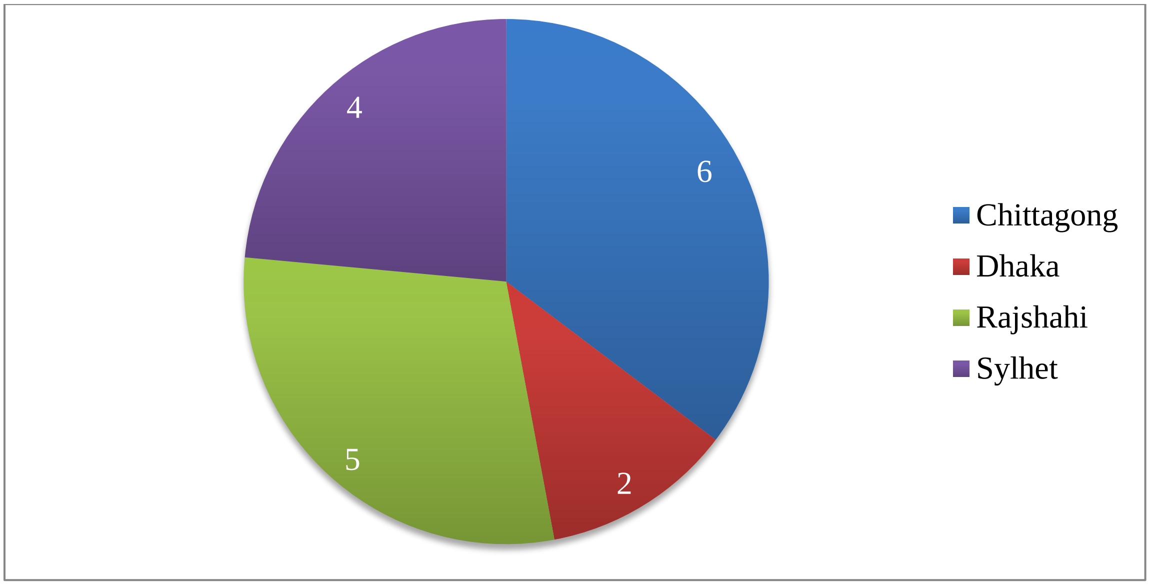


Figure 6. Distribution of partner organization sales representative survey in four different divisions of Bangladesh. The numbers in the pie wedges indicate the number of surveys conducted in the respective regions.

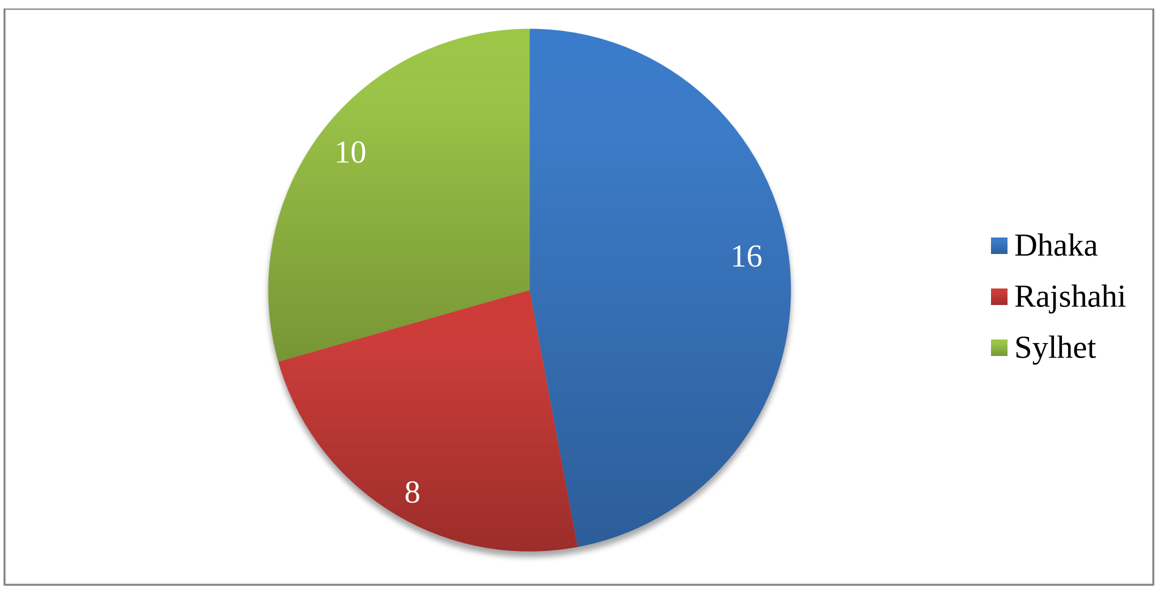


Figure 7. Distribution of shopkeeper surveys conducted in three different divisions of Bangladesh. The numbers in the pie wedges indicate the number of surveys conducted in the respective regions.

The retailer surveys were mostly conducted in selected commercial areas of the respective divisions where sales volumes of LED lamps were expected to be relatively high.

Districts and Areas Surveyed

Data were collected through field interviews with the two groups, in different cities and villages in Bangladesh. The cities and villages were selected based on the size of the SHS market in the respective regions. According to data provided by IDCOL, the distribution of sales of SHS was not even among the seven divisions of Bangladesh. Dhaka Division had the highest sales in the country. Cities and villages under the Dhaka Division were therefore given priority over other potential data collection sites. The interviews of shopkeepers and PO representatives provided information about LED lamps that were available in the market and about reported quality issues associated with the lamps. Table 2 includes the percentage values of the distribution of sales of IDCOL SHS among the seven divisions of Bangladesh. This information helped me select the areas to conduct surveys.

Table 2. The distribution of sales of IDCOL SHS, among the seven divisions of Bangladesh (Haque, 2016).

Division	IDCOL SHS Sales in Percentage
DHAKA	22%
CHITTAGONG	21%
KHULNA	17%
BARISAL	14%
SYLHET	12%
RAJSHAHI	8%
RANGPUR	6%

Dhaka Division

Dhaka is the capital of Bangladesh, and it has many areas where electrical and electronics shops sell LED lamps that can be used with SHS. The city is located in central Bangladesh at 23°42′N 90°22′E. The PO sales representative surveys were done in the districts of Dhaka and Manikganj within the Dhaka Division. For shopkeeper surveys, three different areas were selected: Nababpur, Gulshan-1, and Dhaka Cantonment (Figure 8). Each market was different from the other and had different types of lamps available for sale. Shops located in the Nababpur area are well known for having a large variety of generic brands from various Chinese manufacturers and for whole-sale distribution of LED lamps.

Figure 8. The photo on the left is the Sundarban Square Super Market in Nababpur, Dhaka. On the right is a typical solar shop in Nababpur (Photo credit: Asif Hassan).

These markets supply LED lamps to smaller markets in areas such as Gulshan-1 and Dhaka Cantonment. In total, fourteen shops in Nababpur, one shop in Gulshan-1, and one shop in Dhaka Cantonment were surveyed. Table 3 represented the total number of surveys conducted with the shopkeepers across three different divisions of Bangladesh.

<u>Chittagong Division</u>

Chittagong Division is located in the southeastern part of Bangladesh, and the city of Chittagong has the largest coastal seaport of the country. A total of six PO sales representative surveys were conducted in two different districts within the Chittagong Division. These districts were Commilla and B. Baria. As noted previously, no shopkeeper surveys were conducted in the Chittagong Division.

Table 3. Number of surveys conducted with shopkeepers in different divisions of Bangladesh.

Division	Area	Number of Surveys	Total Number of Surveys
Dhaka	Nababpur	14	16
	Gulshan -1	1	
	Dhaka Cantonment	1	
Rajshahi	Shaheb Bazar	4	8
	Rani Bazar	3	
	City Market	1	
Sylhet	Jindabazar	4	10
	Lal Bazar	4	
	Bandar Bazar	1	
	Jail Road	1	

<u>Rajshahi Division</u>

A total of five PO sales representative surveys were conducted in two different districts, which were Natore and Rajshahi under the Rajshahi Division. The City of Rajshahi is known as a metropolitan city of Bangladesh and is located in the northern side of the country. Unlike the shopkeeper markets of Dhaka, there was little presence of LED lamps in the local markets of Rajshahi (Figure 9).

Figure 9. Some of the retail shops surveyed in Rajshahi. On the left is a solar shop in Rani Bazar. On the right is an electronics shop in Shaheb Bazar (Photo credit: Asif Hassan).

Although there were some shops that sold LED lamps, the number was fairly low. Shopkeeper surveys were conducted in three different areas including Shaheb Bazar, Rani Bazar, and City Market in the City of Rajshahi. Out of the total eight shopkeeper surveys conducted in Rajshahi, four were conducted in Shaheb Bazar, three were in Rani Bazar, and one was in City Market (Figure 10).

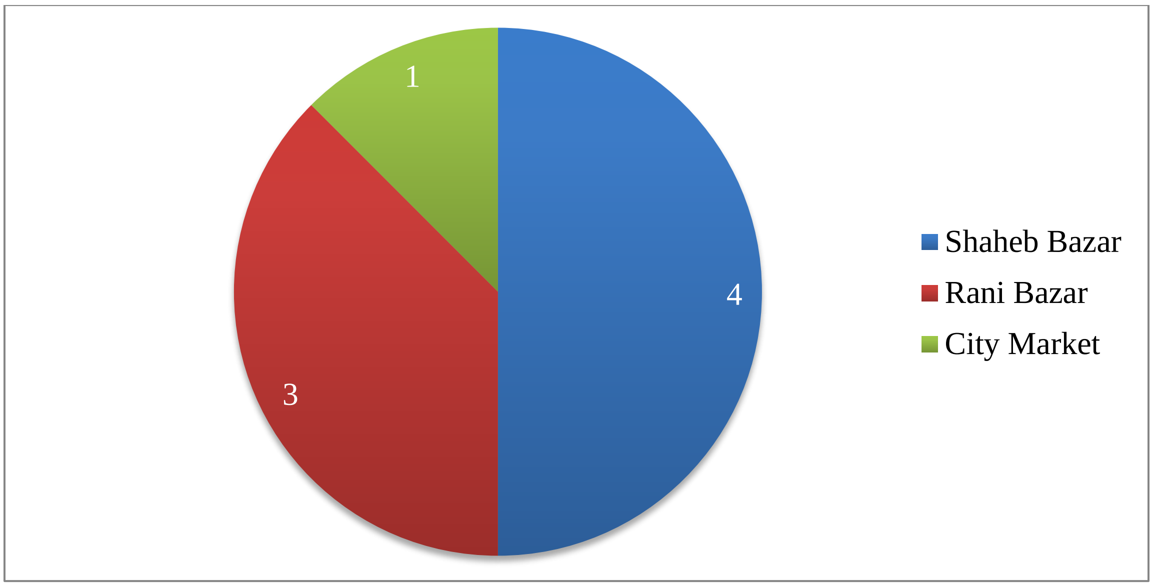


Figure 10. Shopkeeper survey conducted in the division of Rajshahi. Three different areas were covered in the survey in this division. The numbers in the pie wedges indicate the number of surveys conducted in the respective regions.

Sylhet Division

The District of Sylhet is located in the northeast part of Bangladesh, and one of the four districts in the study fell under Sylhet Division. For Sylhet Division, all sales representative surveys were conducted in the main city. Four PO sales representative surveys were conducted in this division. Similar to Dhaka Division, the local markets of Sylhet had a variety of generic brands associated with Chinese manufacturers. Both whole-sale and retail-sales were commonly made in most of the shops (Figure 11).

Figure 11. Some of the retail shops surveyed in Sylhet. On the left is an electronics shop in Bandar Bazar, and on the right is a solar shop in Lal Bazar (Photo credit: Asif Hassan).

A total of ten retail shopkeeper surveys were conducted in four different areas in Sylhet, including Jinda Banzar, Lal Bazar, Bandar Bazar, and Jail Road (Figure 12)

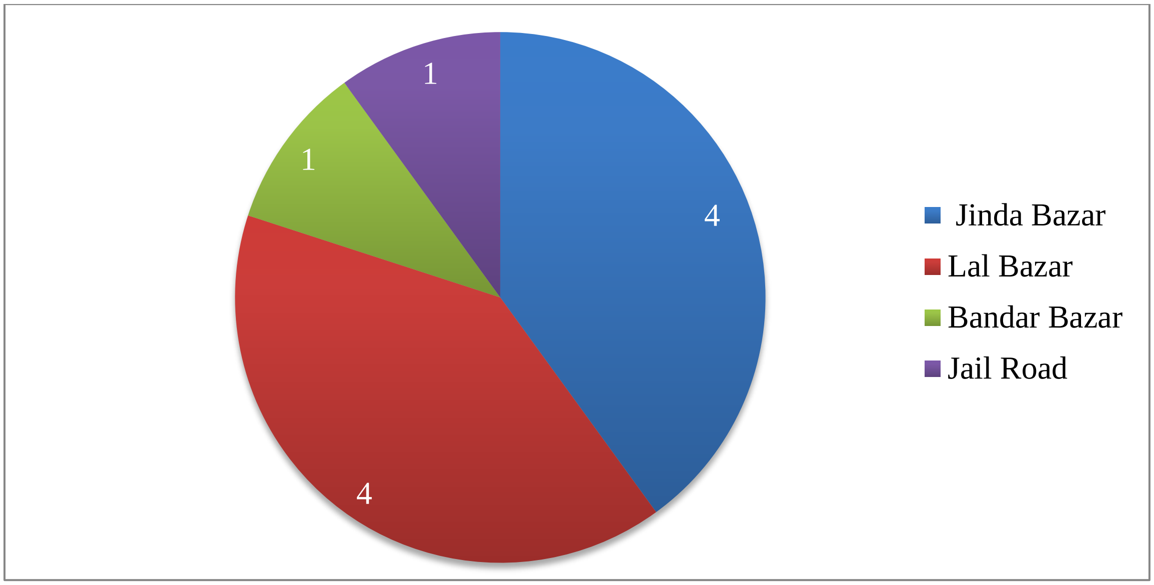


Figure 12. Shopkeeper survey conducted in the Division of Sylhet. Four different areas were covered in the survey in this division. The numbers in the pie wedges indicate the number of surveys conducted in the respective areas.

It can be said that the local LED markets of Sylhet were bigger that the LED markets in Rajshahi. Many more shops and types of LED lights were available in Sylhet compared to Rajshahi. However, Dhaka Division had the largest availability of LED lamps in the Bangladesh solar market among the markets that were observed in this study.

Partner Organizations Surveyed

At the time of the survey, there were forty-seven different partner organizations actively working in Bangladesh solar market. They all had their branch offices in different parts of the country. In recent times, LED lamps had become an integral part of solar home system business in Bangladesh. Based on the sales report for the month of

April, 2015, seven top leading distributors for LED lamps in Bangladesh were selected for the fieldwork. They were Grameen Shakti (GS), Rural Services Foundation (RSF), Upokulio Biddutayan O Mohila Unnayan Samity (UBOMUS), Bright Green Energy Foundation (BGEF), Thengamara Mohila Sabuj Sangha (TMSS), Patakuri, and Integrated Development Foundation (IDF) (Figure 13).

Figure 13. Asif Hassan conducting survey with PO sales representatives. On the left is the Grameen Shakti (GS) branch office in Manikganj. On the right is the GS divisional manager’s office in Natore (Photo credit: GS office staff).

Table 4. Number of surveys conducted with PO sales representative in different divisions of Bangladesh.

Division	City/District	Area	Partner Organization Names	Number of Survey Conducted
Dhaka	Manikganj	Singair	GS, TMSS	2
Rajshahi	Natore	Bonpara	GS, TMSS	2
Rajshahi	Natore	Boraripara	GS	1
Rajshahi	Rajshahi	Baghmara	Patakuri, RSF	2
Sylhet	Sylhet	Uposahar	GS	1
Sylhet	Sylhet	Golapganj	Patakuri, RSF, BGEF	3
Chittagong	Commilla	Homna	UBOMUS	1
Chittagong	B.Baria	Bancharampur	UBOMUS, Patakuri, IDF, BGEF, RSF	5

These partner-organizations helped me to identify major manufacturers and purchasing centers for the LED lamps. PO sales representatives provided information about their respective products, and many of the PO representatives also provided information about LED lamps in local retail markets. Among the seven leading POs, Grameen Shakti (GS) had the largest number of branch offices in the country. I visited 17 different branch offices in total, including four of GS, three of RSF, three of Patakuri, two of UBOMUS, two of BGEF, two of TMSS, and one of IDF (Figure 14).

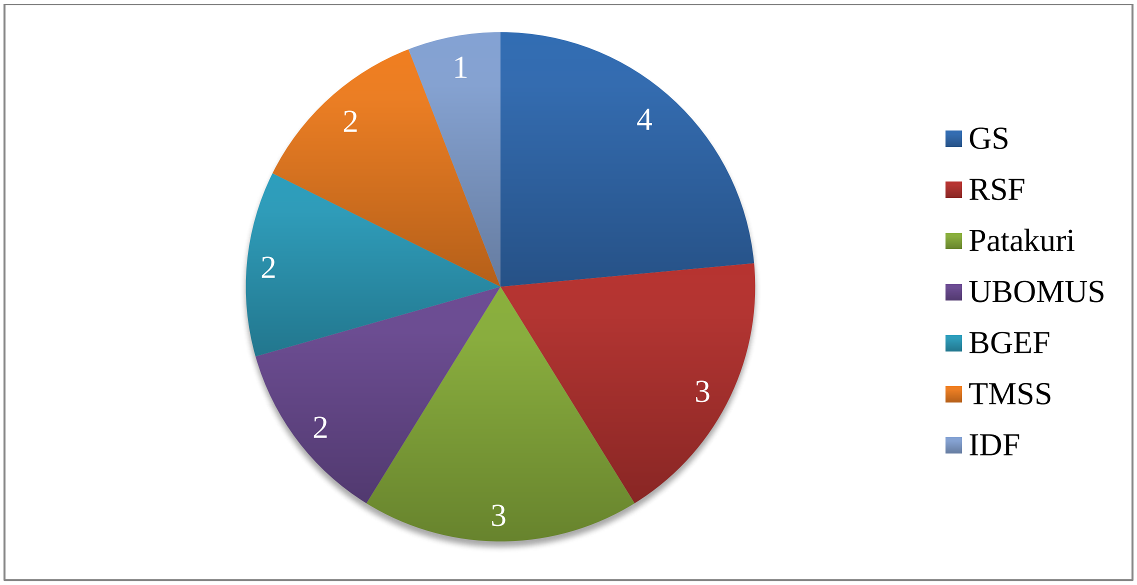


Figure 14. Number of different partner organization branch offices visited to complete the sales representative survey. In total seven teen different PO branch offices were visited. The numbers in the pie wedges indicate the number of surveys conducted in the respective PO branch offices.

Some of the POs did not have any branch office in the selected cities or areas that were chosen for the survey work. Therefore, the number of PO sales representative surveys was not equal across the various areas visited. All of the branch offices of a given PO received the same types of LED lighting products (i.e. the same lamp brand and model) in a particular period of time from their respective ware houses. According to my observations, the exact same lamp brand was available in most of the branch offices for a particular PO. This made the decision making for sample collection easier. I had to decide about the different categories of lamps, the total number of samples to purchase, and the procedure for purchasing the lamps before I initiated the process for collecting samples. Some of the lamps that were selected were tested with a sample size of three (n=3) while others had a sample size of one (n=1). Overall, a total of 156 LED samples were collected from Bangladesh solar market from 32 different product models, including 13 models that were sold by IDCOL POs and 19 models that were sold by shopkeepers. I chose to use a sample size of one for many of the lamp types in order to maximize the number of different products covered in the study. In a limited number of cases, I increased the sample size to three in order to gain an understanding of performance variability for at least some of the available product models. More photos from the fieldwork have been included in the photo gallery section of appendix E.

Labeling and Wiring

The first step for laboratory testing was to label all the samples following a standard labeling format. Sample LED lamps and their packaging received the same label. This step was crucial to make sure the samples were not mixed with each other. Samples were kept in different boxes, which were tagged accordingly. Thus, IDCOL-approved products were kept separate from local-market products. Nine units of each product models were needed to conduct each test at a sample size of n=3 because some of tests are destructive and because it is good practice to collect spare samples in case something goes wrong during the testing process. For products with a sample size of three (n=3), product samples were labeled from one to nine. Similarly, three units of each products were needed to conduct each test at a sample size of n=1. For a sample size of one (n=1), product samples were labeled from one to three. Finding the appropriate sockets to accommodate bulbs that had a three-pin base was an obstacle for testing because these sockets are not commonly used in United States where the laboratory was located. Neither IDCOL-approved LED bulbs nor local-market LED bulbs were supplied with sockets. Most of the LED tube lights were of the three pin type, but some of them were of the two pin type. The next step was to wire the samples. Wiring was categorized into two different segments, which were lumen maintenance wiring and general product wiring. Once the lumen maintenance wiring was done, lamps were ready to begin lumen maintenance testing. For laboratory testing with a sample size of three, samples one, four, and seven were used for the light output test, samples two, five, and eight were used for the lumen maintenance test, and samples three, six, and nine were spare samples. With a sample size of one, sample one was used for the light output test, sample two was used for the lumen maintenance test, and sample three was the spare. Having backup or spare LED lamps was important for laboratory testing, since some samples were defective and one sample broke during testing. Therefore, it was recommended to have backup LED samples.

Product Code

Thirty-two different products were tested in the laboratory. Out of these 32 products, 13 were approved by IDCOL and 19 were collected from local-market shops. The IDCOL-approved lamps were encoded as products IA, IB, IC, ID, IE, IF, IG, IH, II, IJ, IK, IL, and IM. Local-market lamps were encoded as products LA, LB, LC, LD, LE, LF, LG, LH, LI, LJ, LK, LL, LM, LN, LO, LP, LQ, LR, and LS. The purpose of the product coding was to maintain the confidentially of the lamp manufacturers while allowing, product results to be identifiable from one test to the next. Out of the 13 IDCOL-approved products, six had a sample size of three, and seven products had a sample size of one. Out of the 19 local-market LED products, four products had a sample size of three, and fifteen products had a sample size of one. To perform comparative statistical analyses it was important to have the same sample size for all of the products. Therefore, results for products with a sample size of three were averaged for the purpose of some comparative analyses. The averaged product results are noted by adding a prime (') symbol to the respective product codes. Product codes for the converted products were IA', IC', IF', IH', IJ', IM', LA', LC', LO', and LP'.

Methods for Testing Lamps

Once the lamps were collected in the field, they were shipped to the Schatz Energy Research Center for laboratory testing. The test procedures used were similar to methods followed by the Quality Assurance (QA) program of the World Bank Group’s Lighting Global initiative. This program has helped support the development of three different test methods for off-grid solar and lighting products. For this particular research, the test methods used were ones that have been published by the International Electrotechnical Commission (IEC) in Technical Specification 62257-12-1 (hereafter IEC TS 62257-12-1). The Schatz Energy Research Center (SERC) manages the Lighting Global QA program on behalf of the International Finance Corporation and World Bank. SERC also receives support for its quality assurance work from the U.S. Department of Energy through its Global Lighting and Energy Access Partnership (Global LEAP). All tests were completed in the testing laboratory of SERC between September, 2015 and February, 2016. Jeffrey Mosbacher, a student assistant at SERC, and I performed these tests.

Laboratory Measurements of LED Lamps

All the LED lamp samples were evaluated using the following set of tests: lumen maintenance, light distribution, light output, color characteristics, and visual screening. These primary tests were used to help determine the quality, durability, and performance of the lamps. A detailed description of the test procedures can be found in IEC TS 62257-12-1. Before starting the main testing, we had to prepare the products. This preparation included minimal rewiring to enable measurement of the respective parameter. It was also important to label each sample to avoid confusion. A brief description of the six performance indicators measures is included below.

Lumen Maintenance

Good quality LED lamps maintain consistent luminous flux over their lifetime. The lumen maintenance test involves periodic measurement of the relative light output from each sample over a 2,000-hour period. During the 2000-hour period, the lamps are kept on using a power supply that delivers a voltage equal to the nominal operating voltage for the lamps. Thus, I made sure that power to the LED arrays did not drift over the 2,000 hour time period. The device used for measuring the relative light output in this study was a 'self-built box-photometer' (Figure 15).

Figure 15. Self-build box-photometer used to perform lumen maintenance tests.

A total of fifty-two lamp samples were categorized in-to four different batches. Batch -1 consisted of five IDCOL-approved bulbs; Batch-2 consisted of 20 IDCOL-approved tube lights. Batch -3 consisted of 16 tube lights collected from local markets, and Batch-4 consisted of 11 bulbs collected from local markets. I used a single box-photometer to test all the lamp samples in order to maintain consistency throughout the process. The lumen maintenance testing began with Batch-1 and finished with Batch-4. For laboratory testing, the time period of 2,000 hours was used as per the guidance provided in IEC TS 62257-12-1. The expectation was lamps would produce at least 90% of their initial light output after 2,000 hours. If the loss was more than ten percent after 2,000 hours, then the lamp was considered to have failed this test. The temperature of the laboratory was kept constant during the duration of testing, and a fan was used to cool down lamps that generated a lot of heat during the testing. A constant voltage value for the power supply that drove the LED lamps was also maintained during the whole duration of testing. The recommended operating voltage value for the LEDs was 12 VDC, and values between 11.9 – 12.1 VDC were acceptable.

Light Output

The light output test involved measurement of the luminous flux for each product. This value is given in lumens, and it is a measure of the total amount of light that a light source produced in all directions. An integrating sphere and programmable DC power supply was used to perform light output tests (Figure 16). While conducting the light output test, the correlated color temperature (CCT), color rendering index (CRI), and input electrical power values were measured. The light output test results were used to calculate the luminous efficacy, which is given in units of lumens per watt. Luminous efficacy values were used as an important metric of the overall quality and efficiency of the LED lamps.

Figure 16. The integrating sphere and programmable DC power supply used to perform light output tests.

This metric provided an indication of the amount of power that was required to attain a certain level of lighting.

Color Characteristics

Color characteristics of lamps were categorized into two sections: correlated color temperature (CCT) and color rendering index (CRI). These two parameters provided information about the quality of the light generated by each product sample. The higher-CCT LED lamps are generally more efficacious than lower-CCT LED lamps, if all the other factors are held constant, due to differences in quantum efficiencies. The CCT values were reported in units of Kelvin (K), while the color rendering index (CRI) results were reported on a scale of 0 to 100, with 100 representing perfect rendering of colors. The lower values of CRI represent incorrect rendering of colors. Therefore, CRI values close to 100 are most desired. This indicates that the lamp renders colors in the same manner as the reference lamp. A CRI value in the 70s is considered acceptable, whereas in the 80s is considered good, and in the 90s is considered excellent. A lighting source with a CRI in the 70s would be acceptable for indoor lighting applications (U.S. Department of Energy, 2012). All the lamps tested in the laboratory were all intended for indoor lighting applications.

Visual Screening

Visual screening was used to assess the trust worthiness of the product packaging and to record product specifications, to record information about the manufacturer, and to evaluate the robustness of the product’s workmanship. The process was used to compare the measured performance of the LED lamps to advertised values for parameters where manufacturers provided rated specifications on product packaging. We had tested thirty-two different samples for thirty-two different LED products. All the outcomes of the visual screening test were documented in a standard visual screening worksheet that is similar to one that is used by Light Global QA.

Light Distribution

The light distribution of products is used to determine how light that is produced by the product is delivered for use in a space. All the lamp samples only had one light output setting, and the standard warm-up time was 20 minutes. Before warming up the lamp samples, both the voltage and current ratings were checked to confirm that the voltage and current delivered to the product were the correct ones according to the test procedures specified in IEC TS 62257-12-1. A fixture was used to keep the position of the light leveled through-out the duration of the test. The distance between the LED die and the measurement grid was 0.75m. The size of the grid was one meter by one meter, with 11 points equally spaced across each row. Light distribution testing was performed in a dark room. For each LED lamp, 121 measurements were recorded. Data were recorded using the Extech Datalogging Light Meter (model 401036-09) [precision 0.01 Lux; accuracy +/- 3% of reading]) (Figure 17).

Figure 17. On the left is the set-up to perform light distribution tests. On the right is the Extech Datalogging light meter used to record the measurements.

A horizontal and vertical rotary test was also performed. Nineteen different measurements were taken for both horizontal and vertical rotary test. The distance between the LED die and the rotary jig was kept at one meter. More photos of the laboratory testing equipment have been included in the photo gallery section of Appendix E.

SURVEY RESULTS

In this section I present results from the field survey, including surveys with PO sales representatives and local-market shopkeepers. PO sales representative and shopkeeper survey results are used for the comparison analysis between IDCOL-approved and local-market LED lamps. This analysis covers all the aspects listed below:

- Presentation of PO and retail shop characteristics (including size of the business, territory covered, when they started selling LEDs, etc.).
- Estimation of the level of variation in product characteristics offered by retail shops and POs.
- Discussion about characteristics of sales offerings by shops and POs (i.e. consumeer credit and guarantee offerings).
- Discussion and analysis of customer priorities and problems experienced.
- Analysis of product pricing.

PO sales representative surveys were used to collect information about the activities of the POs, the products that they sold, and the feedback they received from their customers. In total, seventeen surveys were conducted across four different divisions of Bangladesh. The survey results enabled me to find out the main factors considered by customers when they purchase a product and the problems that they experienced and then conveyed back to the PO sales representatives with regard to LED lamps. Table 5 and Table 6 respectively represent information collected through PO sales representative and shopkeeper surveys. Parameters listed for POs include warranty terms, total number of customers, and the area covered by the PO branch office. Similarly, parameters listed for retail shops include shop type, sales type, and number of employees working in the shop. The shopkeeper surveys also provided information about their business practices, the products that they sold, and feedback they had received from customers. In total, thirty-four surveys were conducted at retail shops across three different divisions in Bangladesh. With regard to customer priorities before purchasing and the problems they reported, the results for the local-market shops indicate some similarities along with some key differences in comparison to the survey results for the PO sales offices.

Table 5. Location and profile of PO sales representatives interviewed during the field study. The 17 sales representative surveys were distributed among four divisions in Bangladesh.

Bangladesh				
Division/Location	Dhaka	Rajshahi	Sylhet	Chittagong
Sample Size	2	5	4	6

All Data	
PO Agents Interviewed	17
Main Factors Considered by Customers When Making a Purchase (%)	
Price	11
Durability	23
Brightness	20
Warranty	43
Light Color	0
Brand of Product	3
Did Not Mention	0
Others	0
Main Problems Reported to PO Sales Agents by their Customers (%)	
LEDs Become Dim	52
LEDs Fail to Operate	33
Breakage from Dropping	5
Failure of a Switch or Connector	0
Did Not Mention	10
Other problems	0
Fraction of Branches Serving Given Number of Customers (%)	
50-99	25
100-499	25
500-999	25
1000+	25
Radius of Circle Representing the Approximate Area Covered by the Branch (%)	
10 km	76
15-19 km	6
20 km	6
50 km	6
100 km	6
Credit & Guarantee Offered (%)	
Both offered	100

Table 6. Location and profile of retail shops interviewed during the field study. The 34 shopkeeper surveys were distributed among three divisions in Bangladesh.

Bangladesh			
Division/Location	Dhaka	Rajshahi	Sylhet
Sample Size	16	8	10
All Data			
Sample Size	34		
Main Factors Considered by Customers When Making a Purchase (%)			
Price	2		
Durability	21		
Brightness	14		
Warranty	42		
Light Color	0		
Brand of Product	0		
Did Not Mention	21		
Others	0		
Main Problems Reported to Shopkeepers by their Customers (%)			
LEDs Become Dim	8		
LEDs Fail to Operate	26		
Breakage from Dropping	0		
Failure of a Switch or Connector	3		
Did Not Mention	63		
Other problems	0		
Shop Characteristics			
Shop Type (%)			
Electrical/Electronics	68		
Supermarket	0		
Solar	32		
Hawker	0		
PO Agent	0		
Other	0		
Sales Type (%)			
Retail	9		
Wholesale	18		
Both	73		
Number of Employees (%)			
1 to 2	62		
3 to 5	38		
6 to 10	0		

PO and Retail Shop Characteristics

The characteristics of the PO branch offices were very similar to one another with regard to the total number of customers, the area covered by the branch, and the power rating of the available LED lamps. Twenty-five percent of the branches had 50 to 100 customers, 25% had 101 to 500 customers, 25% had 501 to 1000 customers, and the remaining 25% had more than 1000 customers. The distribution of the customers of these branches was very even (Table 5). A majority of these branches covered a circle area that has a radius of ten kilometers (km) and sold lamps of different ratings (e.g. 2W, 3W, 5W). Out of all the retail shops, 68% were electrical and/or electronics shops and 32% were specialty solar shops. In a solar shop, all components of SHS along with LED lamps were available. Only nine percent of shops sold lamps exclusively on retail basis, and 18 percent of the shops sold lamps only on a wholesale basis. The majority (73%) of the shops indicate that they sold products on both a retail and wholesale basis according to the demands of their customers. The majority (62%) of the shops had one to two employees , and the rest (38%) had three to five employees. This indicates that most of the shops were small in size. The local-market shops had LEDs of different ratings (e.g. 2W, 3W, 5W, 6W, 7W, 8W, 9W).

LED lamps are comparatively new to Bangladesh solar market. With the help of the survey, I tried to find out when the partner organizations and local-market vendors started selling LED lamps. The majority (77%) of the POs had been selling LED lamps for the last three years, and another 23% for the last three to six years. (Figure 18). On the other hand, a number (29%) of the shopkeepers had been selling LEDs for the last two years, 12% for the last one year, 3% for the last one and half years, 3% for the last three months, and another 12% for the last three to six years. But another good number of shopkeepers (26%) did not mention from when they started selling LED lamps. A small number (6%) had been selling LEDs for the last three years, and a further nine percent had been selling LEDs for more than six years (Figure 19).

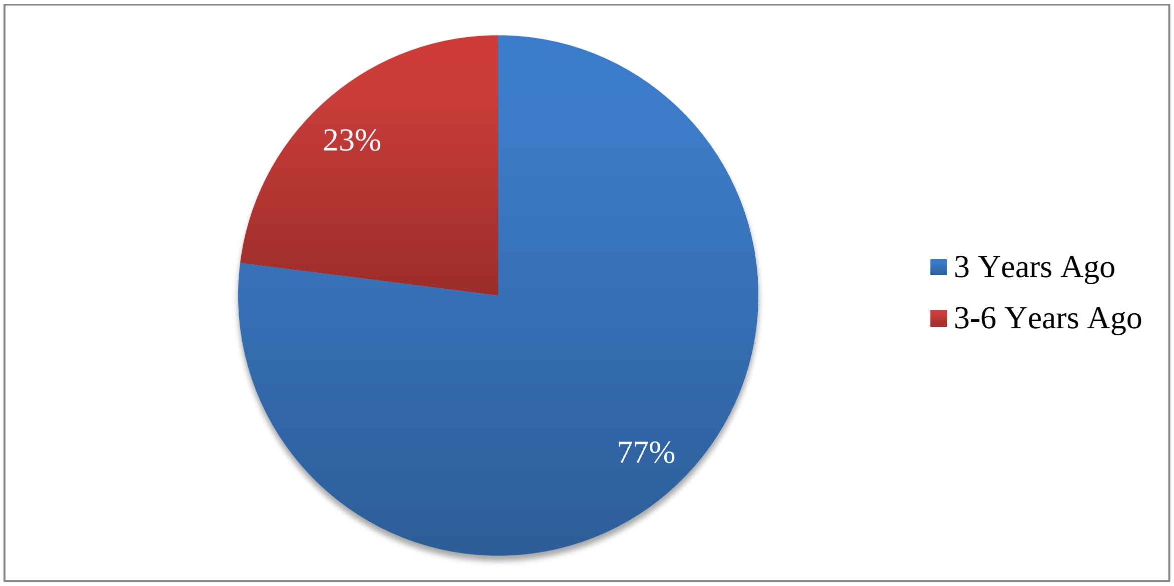


Figure 18. Time when the partner organizations first started selling LED lamps. The numbers in the pie wedges indicate the percentage of POs that first started selling LEDs in the indicated time period.

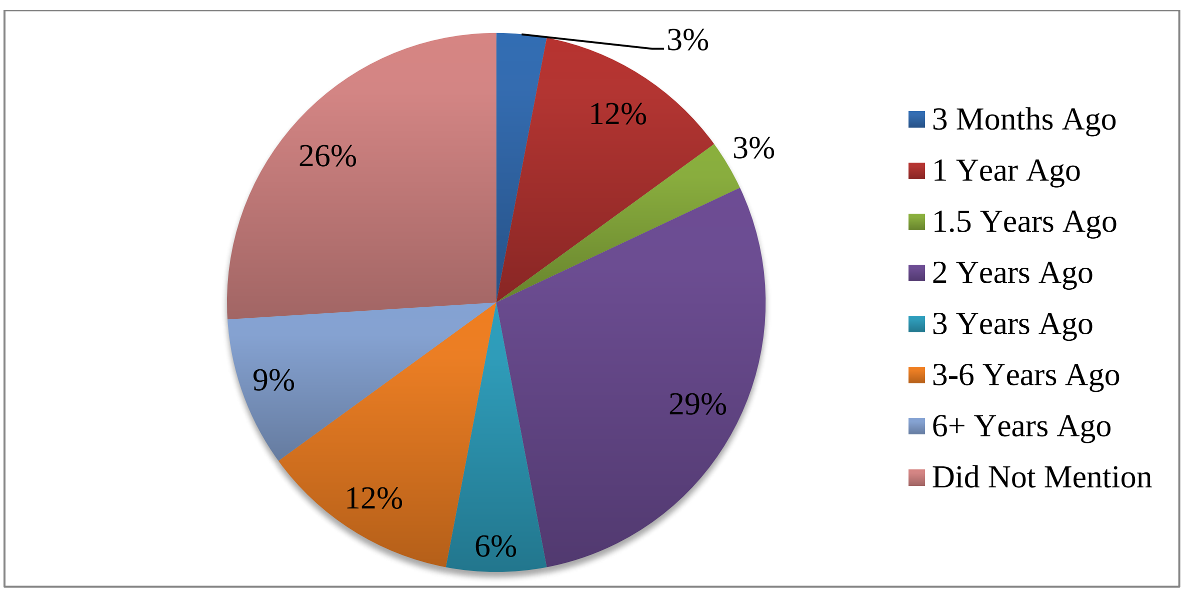


Figure 19. Time when the local-market vendors first started selling LED lamps. The numbers in the pie wedges indicate the percentage of shopkeepers that first started selling LEDs in the indicated time period.

From Figures 18 and 19, it is evident that all of the POs and most of the shopkeepers first started selling LEDs within the last six years. Therefore, LED technology was still very new to the Bangladesh solar market.

Characteristics of Products Offered by POs and Retail Shops

The majority (78%) of the branches sold LED tube lights or bulbs that were rated at three watts. Only 11% of the branch offices sold tube lights or bulbs that were rated at five watts, and about 6% of the branch offices sold both three and five watt lamps at the same time (Figure 20). As required by IDCOL, partner organizations provided customers a three-year warranty period for all the LED lamps. In addition, they also offered a credit option to customers. LED lamps were sold with the solar home systems packages. All customers were eligible to apply for credit to purchase the SHS including lamps. They could also buy the lamps separately if they had already purchased the SHS package from the same branch office.

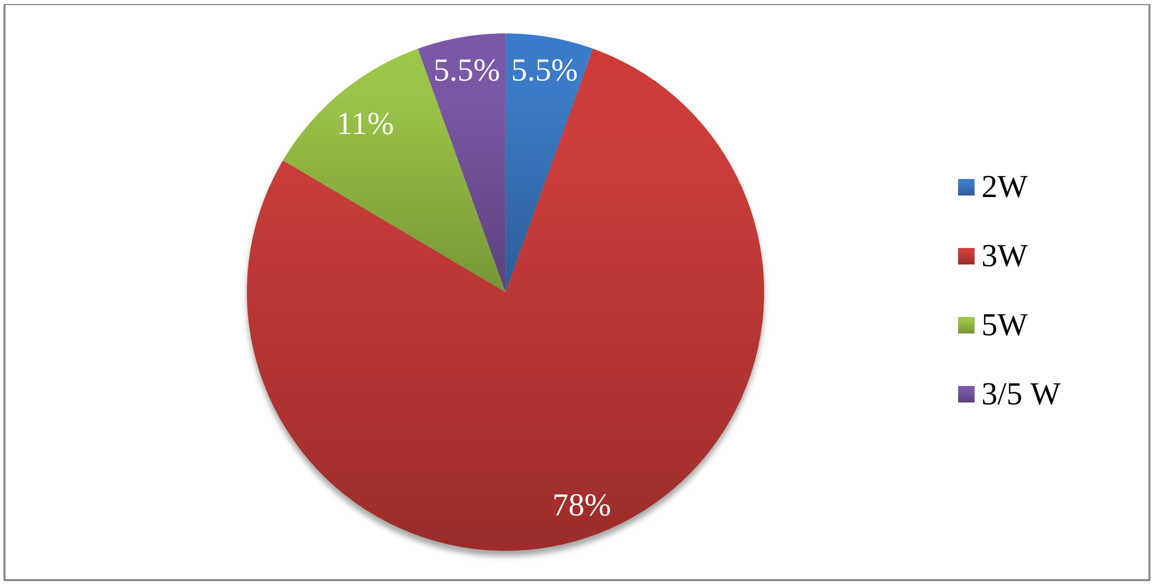


Figure 20. Percentage of different power ratings of IDCOL-approved LED lamps. The majority of the lamps were rated at three watts. The numbers in the pie wedges indicate the percentage of different power ratings.

From Table 6 is was evident that many (44%) shops sold LEDs rated at five watts and another 42% sold LEDs that were rated at three watts. Some shops sold lamps of multiple ratings (Figure 21).

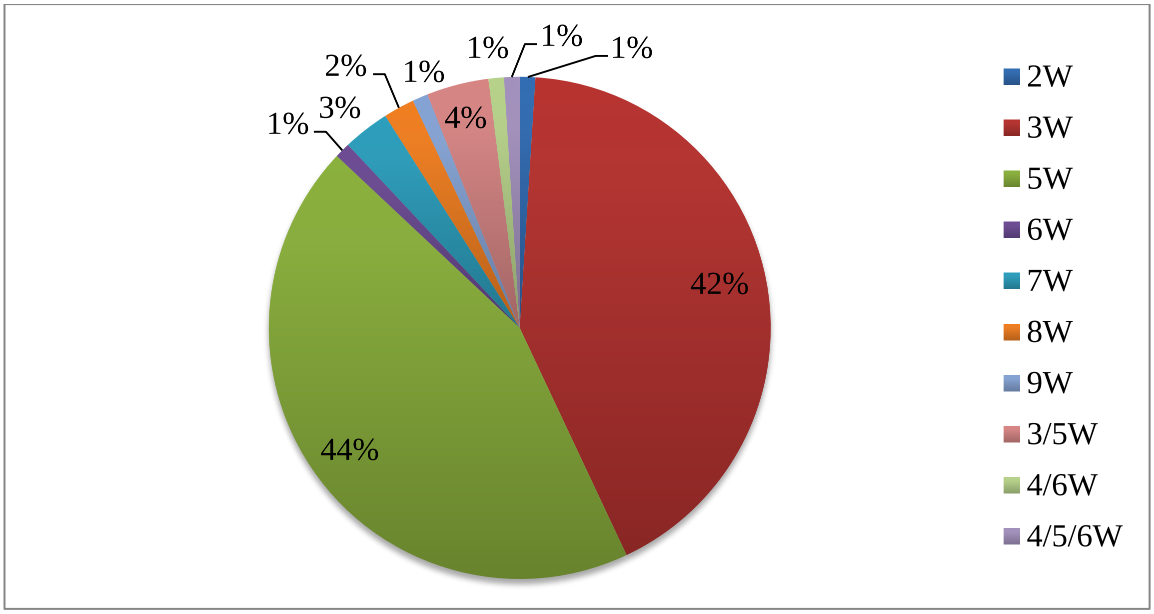


Figure 21. Percentage of different power ratings of local-market LED lamps. The local-market shops had LEDs of different ratings. The numbers in the pie wedges indicate the percentage of different power ratings.

One of the differences between the IDCOL-approved lamps and the local-market lamps was the warranty period. Many of the retail shops (44%) did not offer any warranty for the lamps they sold, while an additional 25 percent of the shops offered warranties for one or two particular types of lamps. Only 14 percent of the shops consistently provided a one-year warranty for their lamps, while six percent provided two-year warranties, and 11% provided three-year warranties (Figure 22).

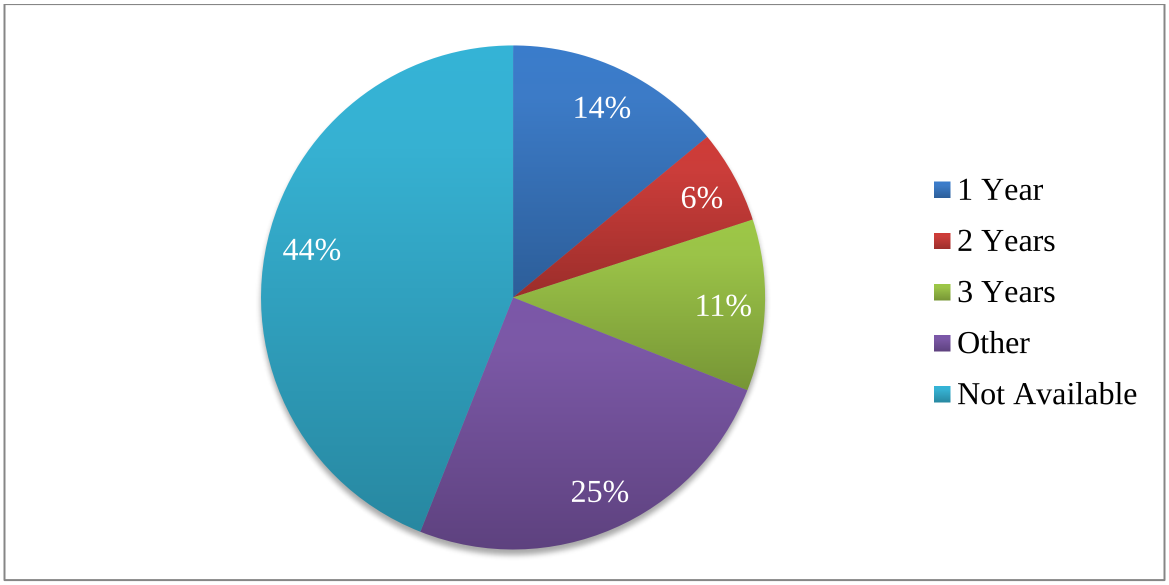


Figure 22. Percentage of different warranty periods of local-market LED lights. The numbers in the pie wedges indicate the percentage of lamps associated with the indicated warranty periods.

The ‘other’ section in the pie chart referred to those shops that only offered a warranty for one or two particular types of lamps that they sold, while not offering a warranty on the other lamps. In addition, most of the shopkeepers were willing to provide warranty at a higher price for the same lamp. One shop indicated that they would spend additional funds to improve the internal circuitry and mechanical aspects of the lamps in cases where a warranty was requested in order to help ensure that the lamps would last longer.

Characteristics of Sales Offerings by POs and Retail Shops

Both PO sales representatives and shopkeepers were asked about the credit and financing that they access to hold stock along with any credit they may offer to their customers. All the POs received credit from IDCOL and provided credit to the customers. All POs (100%) provided both a guarantee on the lamp and credit-based sales to their customers as part of their product offering. The responses from the shopkeepers were very different. Most of the shops did not receive financial support or provide any sort of financial help to their customers. Only three percent of the shopkeepers offered both credit and warranty to customers. In addition, 23.5% of the shopkeepers offered a warranty, but not credit, to their customers. Most shopkeepers used the term guarantee instead of warranty. The word guarantee is more commonly used, but it has the same meaning as a warranty. In addition, warranty was offered on some lamps only. Unfortunately, the majority (70.5%) of the shopkeepers offered neither credit nor warranty to customers (Figure 23).

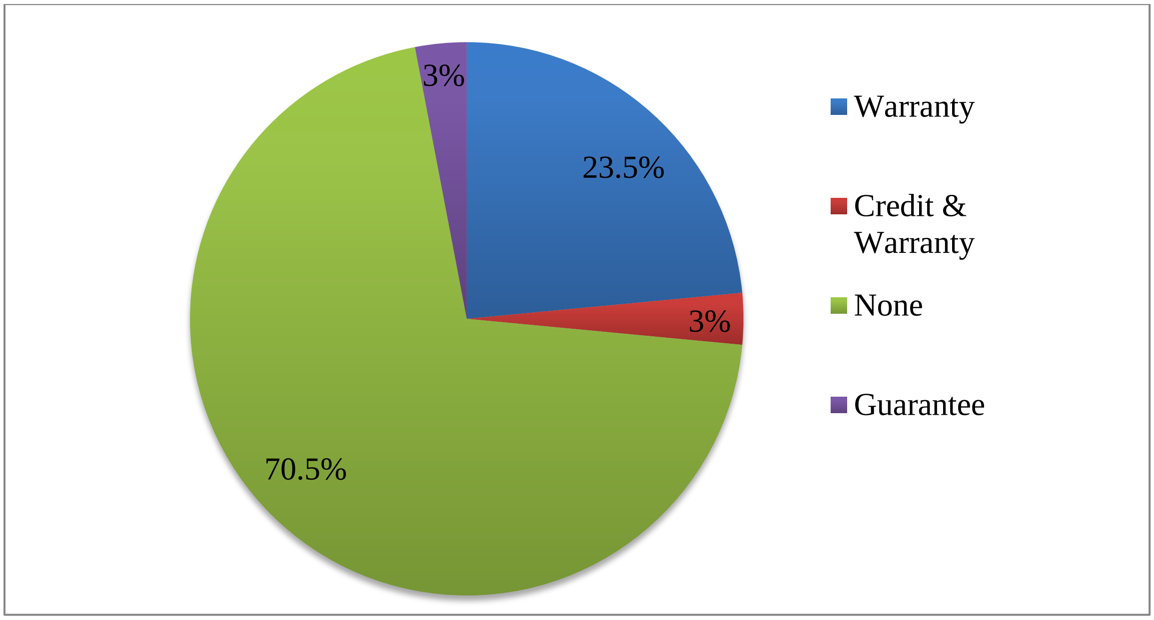


Figure 23. Percentage of credit and warranty offered by the shopkeepers for local-market LED lamps. The numbers in the pie wedges indicate the percentage of shops that offered credit and warranty terms to their customers.

The only sources of credit and financing for the shopkeepers were personal laons from banks and friends/families. The IDCOL solar market was therefore more financially stable than the local solar market. Some sort of financial help would enable the shopkeepers to import and sell better quality of LEDs. This could bring balance in quality between both markets. The partner organizations were only allowed to sell IDCOL-approved LED lamps. Therefore, all the IDCOL-approved lamps should have had IDCOL's logo on their packaging along with other information. A substantial number of lamps (34%) sold by POs did not have IDCOL's logo on the packaging. Only 66% of the products had the logo on the packaging. The logo is important as it is one of the key indicators of IDCOL's approval (Figure 24).

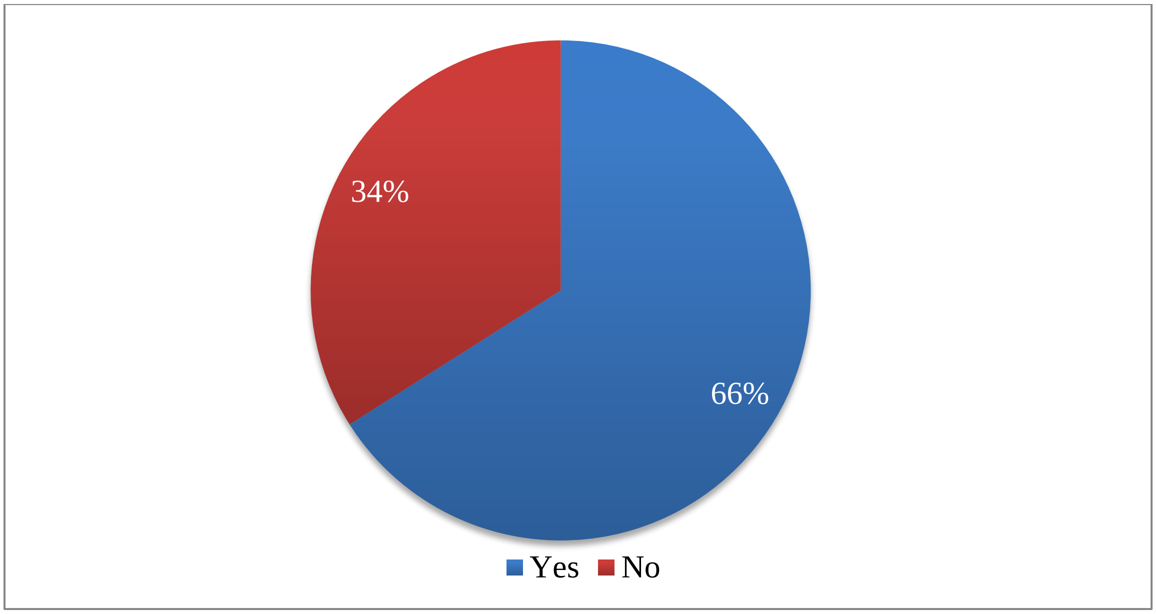


Figure 24. Availability of the IDCOL's logo on the cover of the IDCOL-approved LED lamps. The numbers in the pie wedges indicate the percentage of availability of the IDCOL's logo.

Customer Priorities and Problems Experienced

The results in Table 5 indicate that many customers focused on warranty (43%), durability (23%), and brightness (20%) of the LED lamps before buying the lamps. Surprisingly, only 11% of the total customers identified price as the main factor of consideration. It is likely that all the customers who bought a lamp considered the price; however, PO representatives did not think that their customers considered price to be the most important factor when making a purchase. With regard to issues experienced with the products, 52% of the respondents indicated that their customers said that the lamps became dim over time, while 33% said the lamps failed to operate, and 10% said that their customers did not mention any problems (Table 5).

From Table 6, it is evident that, according to shopkeepers, the majority of the customers focused on warranty (42%), durability (21%), and brightness (14%) before buying the LEDs from the local market. A significant fraction of shopkeepers (21%) did not mention any particular reason cited by their customers, and only two percent of shopkeepers reported that their customers considered the price of the lamps as the primary factor of concern before buying them. The relatively low prices of the LED lamps sold in the local-market shops could be one reason for this small percentage. In addition, customers commonly bargain with shopkeepers to achieve a lower price. From the surveys of the retail shops it was observed that eight percent of the shopkeepers reported that their customers said that the LEDs became dim, 26% said the lamps failed to operate, and 63% said that their customers did not mention any problem (Table 6).

Analysis of Product Pricing

In price analysis section, I will analyze the difference between the prices of IDCOL-approved and local-market LED lamps. The prices of approximately 97% of the local LED lamps were below Bangladeshi Taka (BDT) 450 ($5.74),[1] and the prices for a small number (3%) were unknown (Figure 25). This means that the majority of the LED lamps were low-cost and available to the customers. The prices ranged from as low as BDT 14 to 450 ($0.18 to $5.74). In fact, 78% of the local lamps were priced below BDT 150 ($1.91), and only a marginal number of products were at a higher price. The prices of local lamps were almost same in all the local markets in different divisions of

Bangladesh. In comparison, the prices of the IDCOL-approved LED lights were much higher.

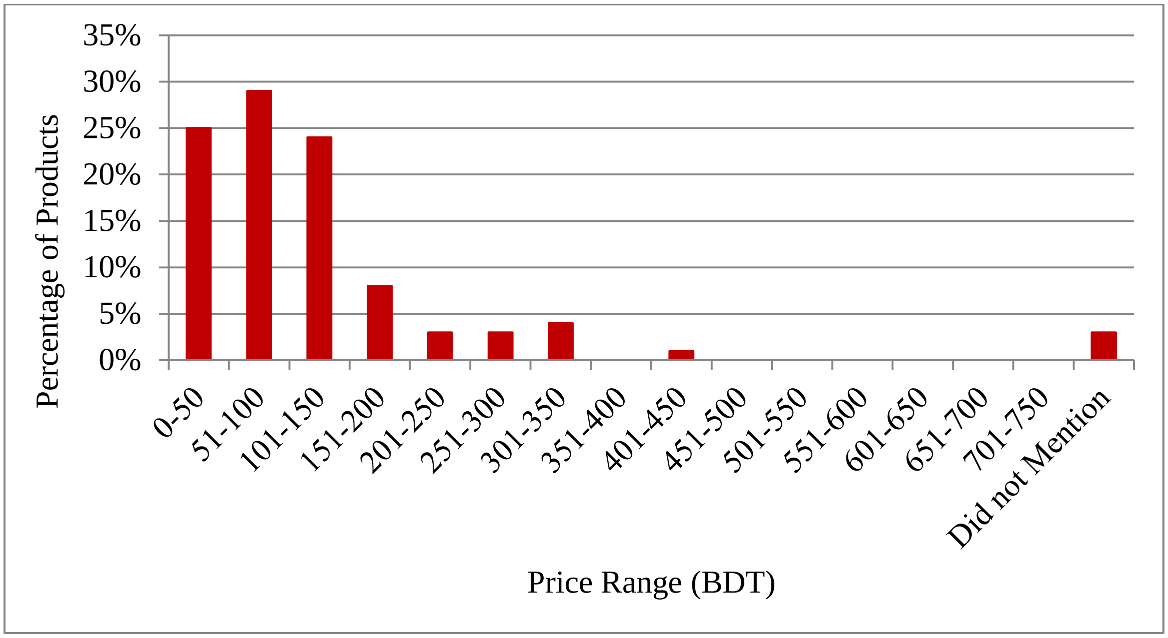


Figure 25. Price breakdown of the local-market LED lamps available in the Bangladesh solar market.

Prices of approximately 67.5% of the IDCOL-approved LED lamps were below BDT 450 ($5.74)[1] (Figure 26), and the remaining 32.5% were in between BDT 401 to 750 ($5.11 to 9.57).

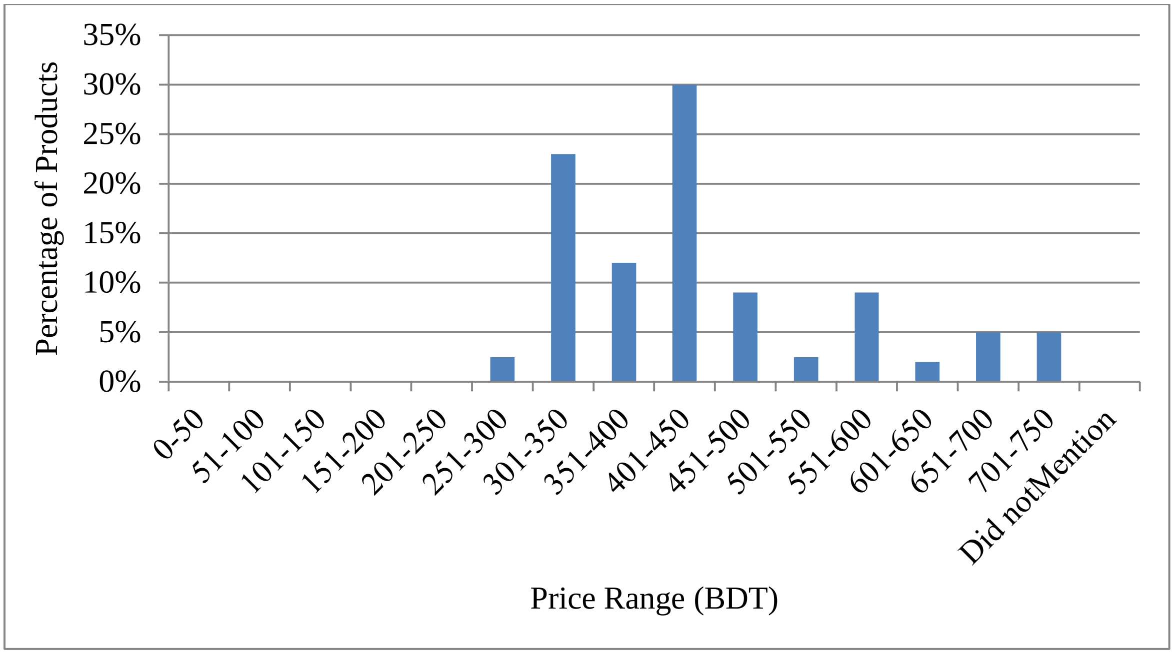


Figure 26. Price breakdown of the IDCOL-approved LED lamps available in the Bangladesh solar market.

This means the majority of the LED lamps sold through the IDCOL POs were more expensive than those available in local markets. The prices of the IDCOL-approved LEDs ranged from BDT 300 to 750 ($3.83 to $9.57). The prices of the lamps varied slightly from one PO to another, but overall the prices for lamps sold by the POs were very similar. The average price of the local-market products was BDT 113 ($1.44), which was considerably lower than the average price for IDCOL-approved lamps BDT 457 ($5.83) (Figure 27).

---

[1] Exchange rate of $1= BDT 78.4 (as on March 21, 2016; Central Bank of Bangladesh)

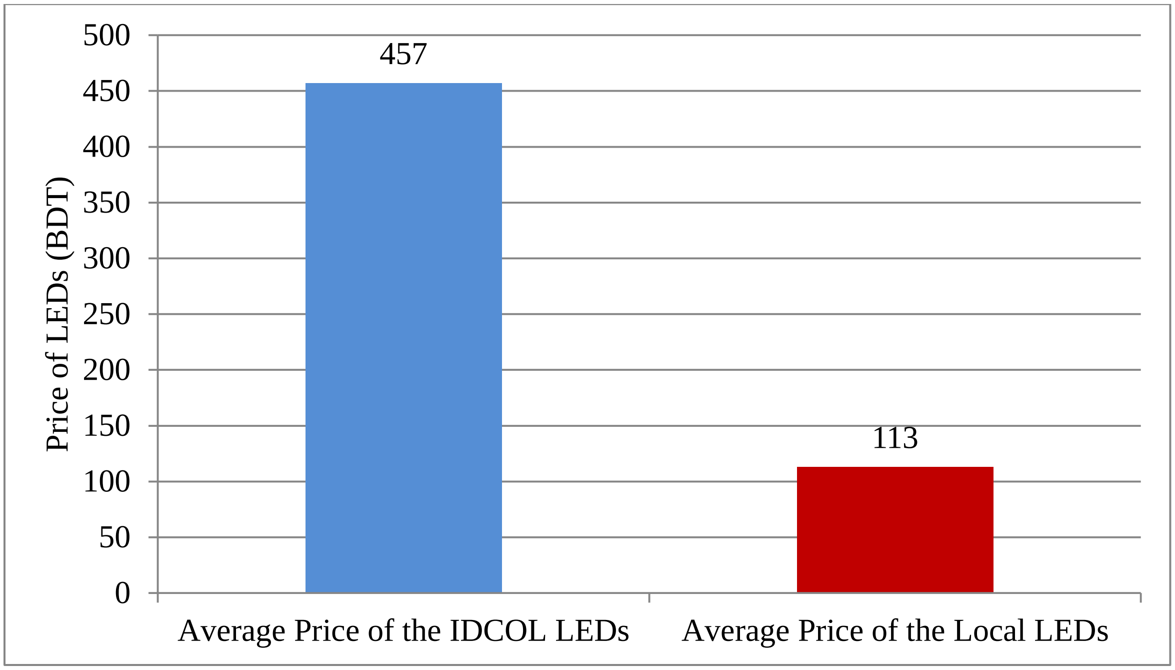


Figure 27. Comparison of average price between IDCOL and local-market LED lamps.

The lowest price ($3.83) of the IDCOL-approved LEDs was 21 times higher than the lowest price ($0.18) of the local-market lamps, while the highest price ($9.57) of the IDCOL-approved LEDs was almost two times higher than the highest price ($5.74) of the local-market lamps. This indicated that there was a more significant difference between the lowest prices of IDCOL-approved and local-market LED lamps.

Price Per Rated Watt for Lamps

The average wattage value for all the local-market LED lamps was 4.2 W, and the average price of the local-market products was BDT 113. Therefore, for local-market lamps, the price per rated watt was BDT (113/4.2) or BDT 26.9. The average wattage value for all the IDCOL-approved LED lamps was 3.2 W, and the average price of the

IDCOL-approved products was BDT 457. Thus, for IDCOL-approved lamps, the price per rated watt was BDT (457/3.2) or BDT 142.8. This indicates clearly that the average price per rated watt for IDCOL-approved LED lamps is much higher than the corresponding price for local-market LED lamps.

Price Per Measured Lumen Output for Lamps

The average lumen output value in laboratory testing for all the local-market LED lamps was 266 lumens. Therefore, for local-market lamps, the price per measured lumen output was BDT (113/266) or BDT 0.42. The average lumen output value for all the IDCOL-approved LED lamp was 269 lumens. Thus, for IDCOL-approved lamps, the price per measured lumen output was BDT (457/269) or BDT 1.7. This metric also confirms that the local-market products are less expensive per lumen, but the ratio between the prices for this metric (5.3 to 1) is not as large as the ratio based on the price per rated watt (4 to 1). These two metrics normalized the prices in a way that made for a more accurate comparison of pricing.

LABORATORY TEST RESULTS

The purpose of the laboratory testing was to measure the quality and performance of LED lamps that were available through IDCOL POs and the local market. This section includes results that allow for a comparison between them. The test results section covers all the aspects listed below:

- Discussion and analysis of the key results from laboratory tests including lumen maintenance, lumen efficacy, light distribution, light output, color characteristics, and visual screening.
- Estimation of the level of variation for key performance indicators between IDCOL-approved LED lamps and lamps collected from local solar market.
- Presentation of results from a technical analysis to calculate the difference in the level of energy service received by households that utilize IDCOL-approved lamps versus lamps from the local market.

Lumen Maintenance

In the lumen maintenance section, results for light output from each LED lamp sample are reported. This section will represent the periodic measurement values of the relative light output from each sample over a 2000-hour period. Figure 28 includes results for LED bulbs from IDCOL POs for the lumen maintenance test. Out of five bulbs tested, only one went below the 90% level. LED tube lights from IDCOL POs showed more consistency than LED bulbs from IDCOL POs, as most of the trend lines were very close to each other. All the samples from the same partner organization have been marked with the same line color. It is easy to identify which products meet the 90% requirement after

2,000 hours by examining the graph. From Figure 29 it was evident that only one product out of 20 tube lights from IDCOL POs went below the 90% level. Figures 30 and 31 respectively present the performance of local tube lights and bulbs. It was notable that results vary widely from one product model to another. For LED tube lights from local market, a majority of the LED lamps had failed within a very short period of time. In fact, one of the lamps stopped functioning entirely before the 2,000-hour mark.

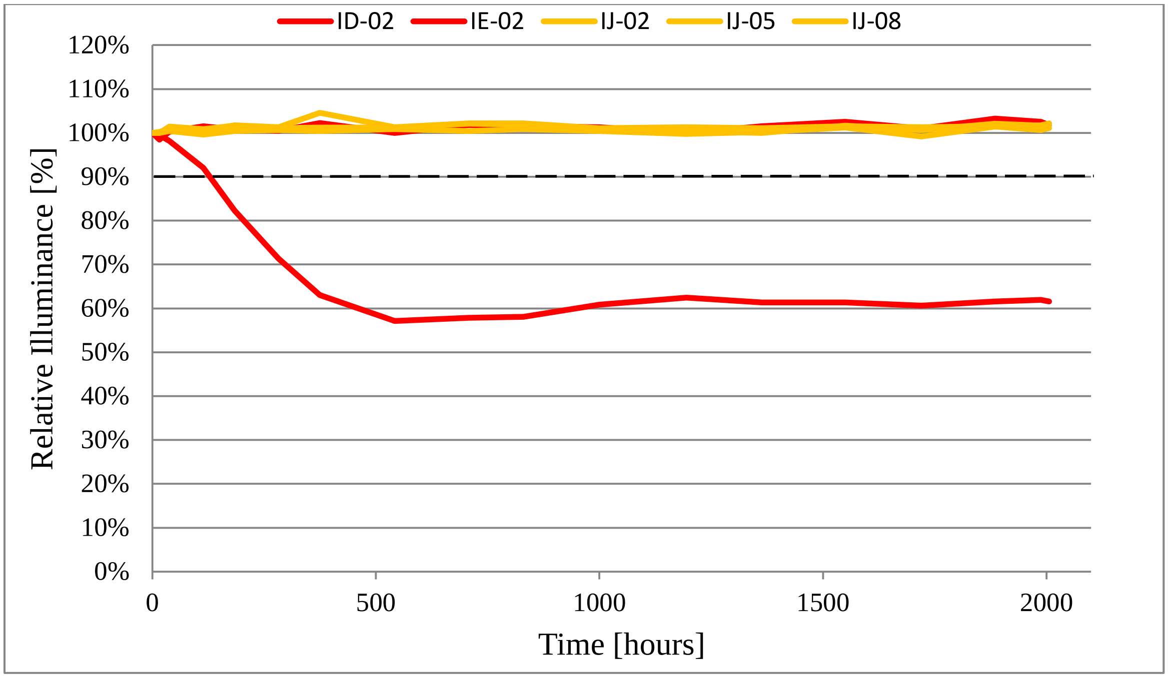


Figure 28. Lumen maintenance result of IDCOL-approved LED bulbs.

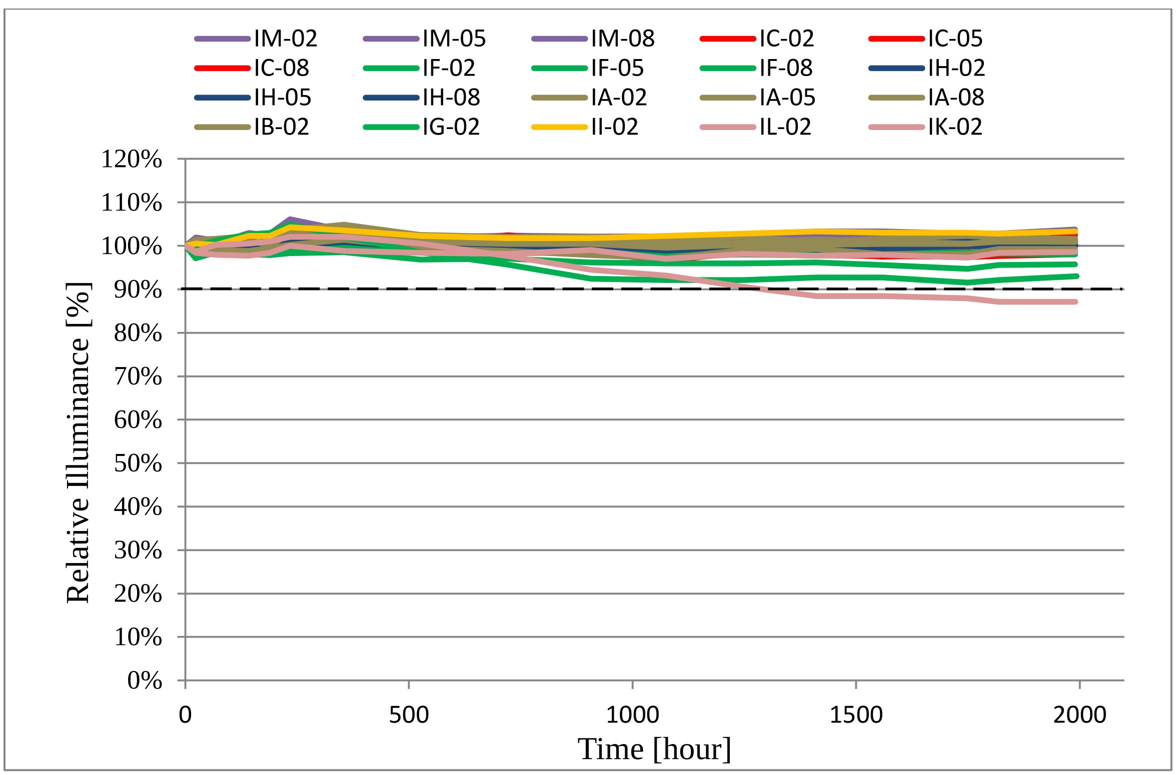


Figure 29. Lumen maintenance result of IDCOL-approved LED tube lights.

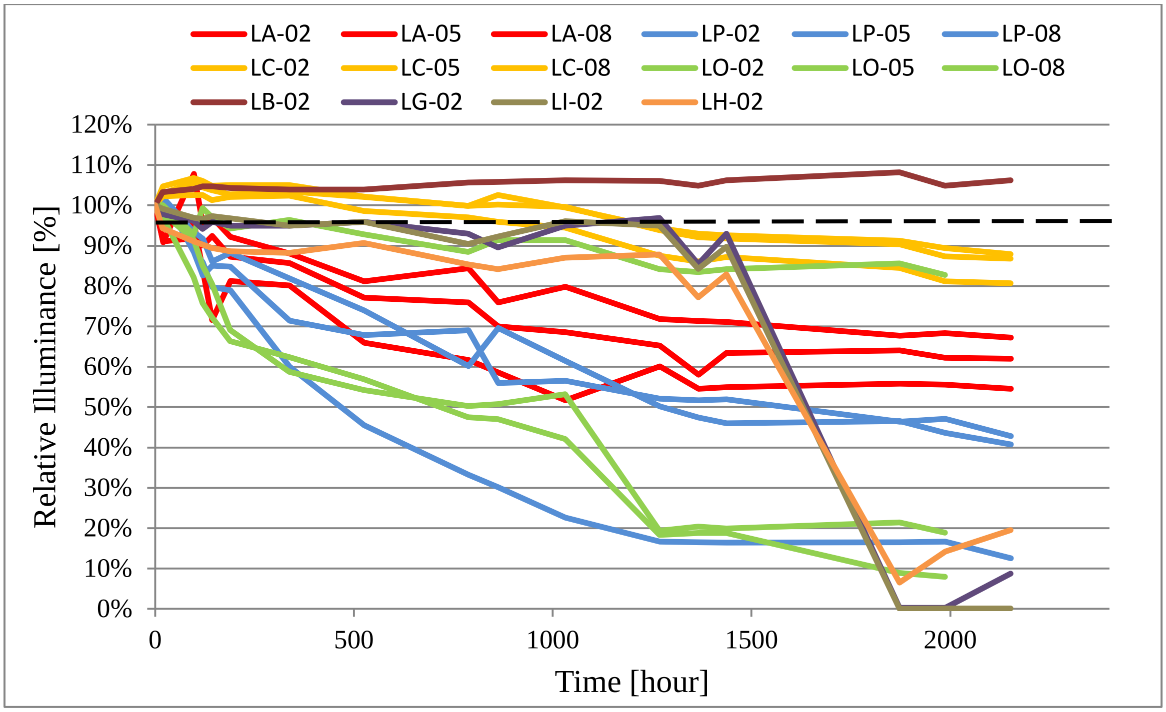


Figure 30. Lumen maintenance result of local-market based LED tube lights.

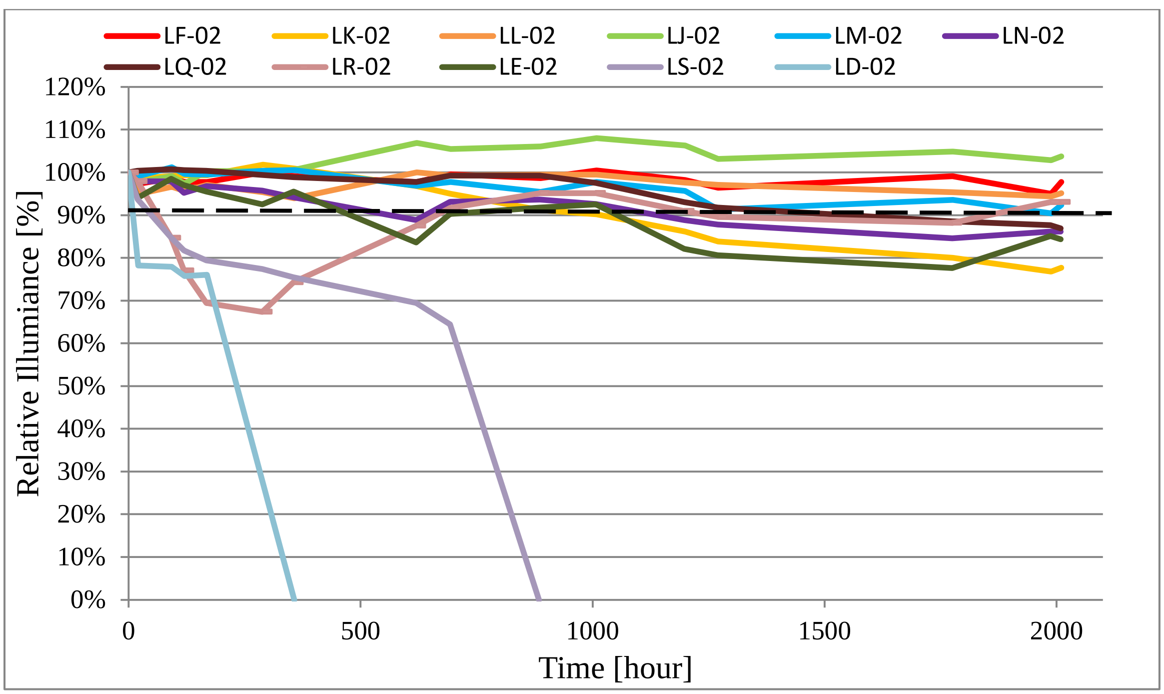


Figure 31. Lumen maintenance result of local-market based LED bulbs.

LED bulbs from the local-market showed better performance than LED tube lights from the local market, but in both cases the lumen maintenance performance was unsatisfactory. The light output for a good number of the lamps fell below 90% of the original light output at a very early phase of the testing. In fact, two samples stopped functioning entirely before half-way mark. While there is room for some improvement among some of the products sold by IDCOL POs, the results for local-market products indicate unacceptably rapid depreciation of light output in a large number of cases. A detailed summary of the lumen maintenance results is included in Tables D-1 and D-2 of Appendix D.

Reasons of Lumen Depreciation

Based on an understanding of technical issues related to lumen depreciation and observations from our laboratory testing, poor quality electronic LED chips and excessive temperature at the LED chip level were the main reasons for depreciation. These LEDs appeared very bright at first, but the level of light output declined within a very short period of time. During testing it was notable that many of the local-market LEDs got very hot. This was evident when making the periodic measurements, as many of the lamps were hot to the touch. There could have been two main reasons for excessive temperature of the chip. First, the LEDs could have been driven with too much current from the product’s current driver circuits, leading to excessive temperature. A second and related issue is associated with the design of the heat sink on the circuit board. LED circuit boards should be able to dissipate the heat generated during lamp operation while maintaining the LEDs within an acceptable temperature range (Lighting Global, 2010).

Prevention of Lumen Depreciation

LED product manufacturers should design the lamps so that they operate below the recommended maximum current and temperature values. Lower drive currents result in lower light output, but the LEDs last longer because they are less likely to overheat. Moreover, the use of improved heat sinks can be used to manage temperature. To increase the light output for a given product, more LEDs can be used and/or better heat sinks can be utilized. Both of these measures may increase the cost of manufacturing, but for a new technology like LEDs, quality should be given priority over cost. In addition, IDCOL and local vendors of LEDs should strongly consider the use of laboratory testing before releasing products into the market. Such test results can provide important information about the quality and durability of their products (Lighting Global, 2010).

Light Output

In this section, results for luminous flux, lumen efficacy, correlated color temperature (CCT), and color rendering index (CRI) are reported. In addition to the measured values and associated averages for the respective metrics, results are also presented that are related to the variability of performance within a product model in cases where a sample size of three was used. Table 7 includes the average values of all the four key performance metrics for both IDCOL-approved and local-market LED products. The sample size actually represented the total number for different IDCOL-approved and local-market products. Using the data from Table 7, similarities and differences between IDCOL-approved and local-market LED products were determined. It is particularly notable that the average values for lumen output, CRI, and CCT were similar between IDCOL-approved and local-market products, but the lumen efficacy values were very different. A detailed summary of all measured results is included in Table C-1, Table C-2, and Table C-3 of Appendix C.

Table 7. Average values for all the four key performance metrics for both IDCOL-approved and local-market products. The number of product models considered is indicated in column “A”.

Source of the Product	Total Number of Product Models	Average lumen output [lm]	Average Luminous Efficacy (lm/W)	Average CRI [-]	Average CCT [K]
All IDCOL LEDs	13	259	83	74	6518
All Local LEDs	19	247	50	75	6776

Key light output performance metrics are also presented graphically in Figures 32 and 33.

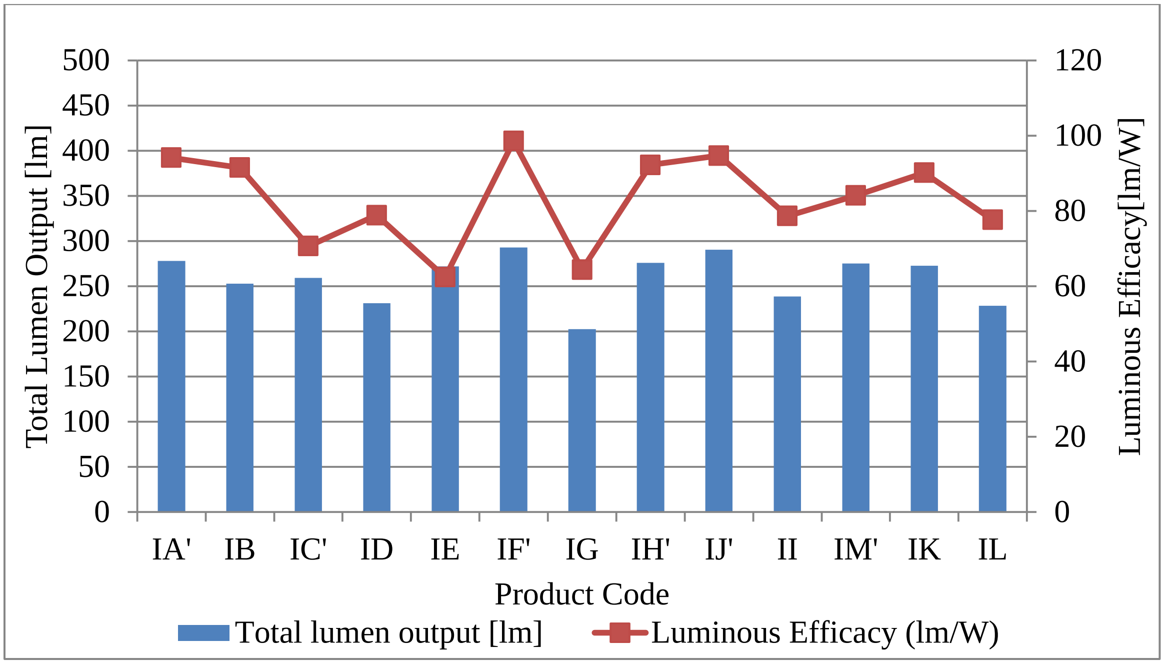


Figure 32. Comparison between total lumen output and luminous efficacy values for all the IDCOL-approved LED lamps.

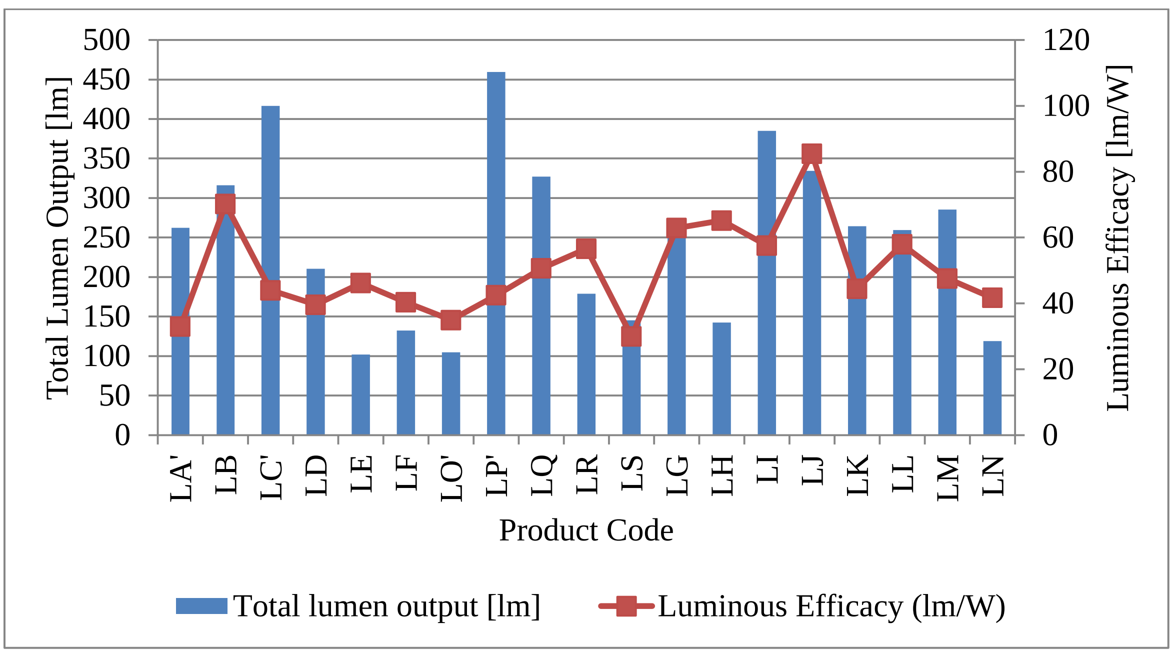


Figure 33. Comparison between total lumen output and luminous efficacy values for all the local-market LED lamps.

As shown in figures 32 and 33, the total lumen output and luminous efficacy values are plotted vs. the product codes in the same graphs using dual axes. This enabled comparison of the performance of the IDCOL-approved and local-market LED lamps. Figure 34 includes all CCT values for both IDCOL-approved and local-market lamps. As shown in the figure, almost all the lamps had similar CCT values. One local LED model, encoded as LN, had a very high CCT value. The color of the lamp was very blue.

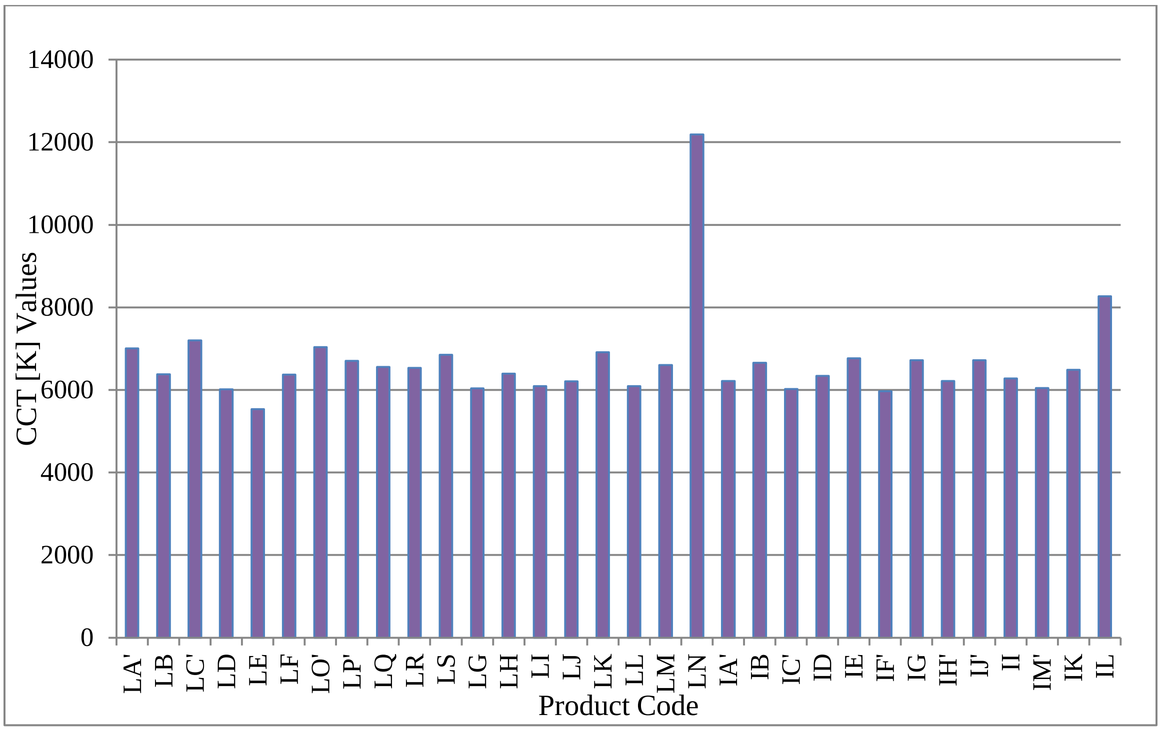


Figure 34. Correlated color temperature values for both IDCOL and local LED lamps.

The desired values for the CCT metric are subjective and depend on end-user preferences. LED lamps with a CCT of 2500 to 4000 K are known as “warm light”. On the other hand, lamps toward a CCT of 6000 K and above are known as “cool light” (Nielsen, 2014). Warmer light is associated with a lower CCT value, and most samples tested in this project had CCT values over 6000K. LEDs with higher CCT values are generally less expensive for a given level of lumen efficacy, and it is likely that the various lamp manufactures are simply sourcing the lower cost LEDs in order to keep their costs down. As most of the products have high CCT values, customers do not have any option to indicate a preference for warmer color temperature LEDs. Consumer research would be needed to gain a more detailed understanding of consumer preferences for light color temperature in Bangladesh. The average CCT values for both IDCOL-approved and local-market lamps are presented in Figure 35. Figure 36 provides a complete graphical representation of the luminous efficacy values of LED lights from both markets.

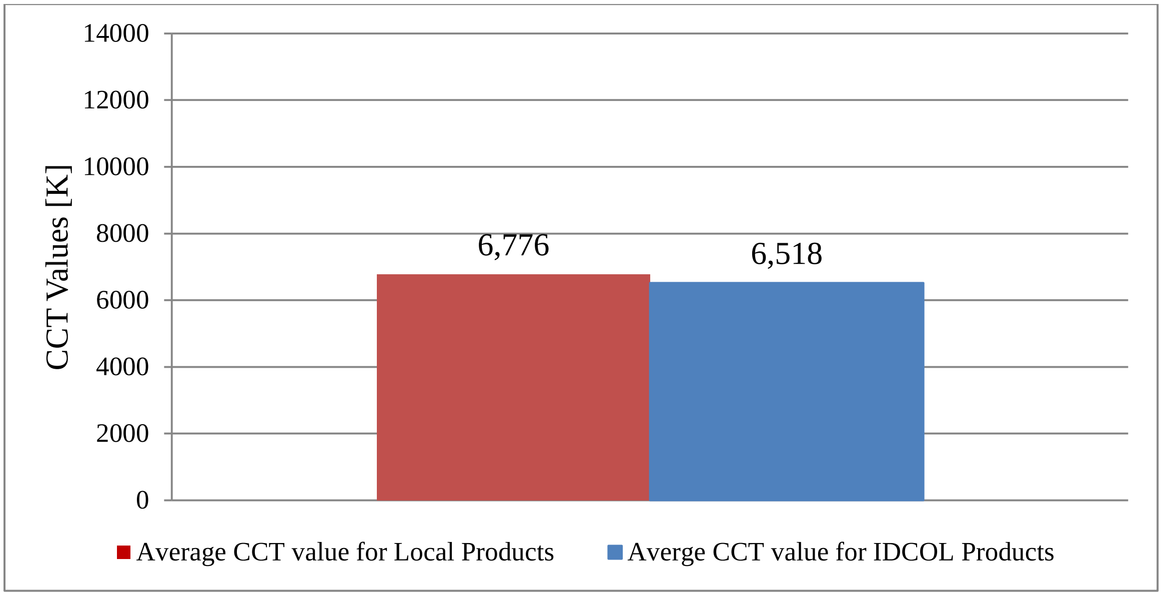


Figure 35. Comparison of average CCT values between IDCOL-approved and local-market LEDs.

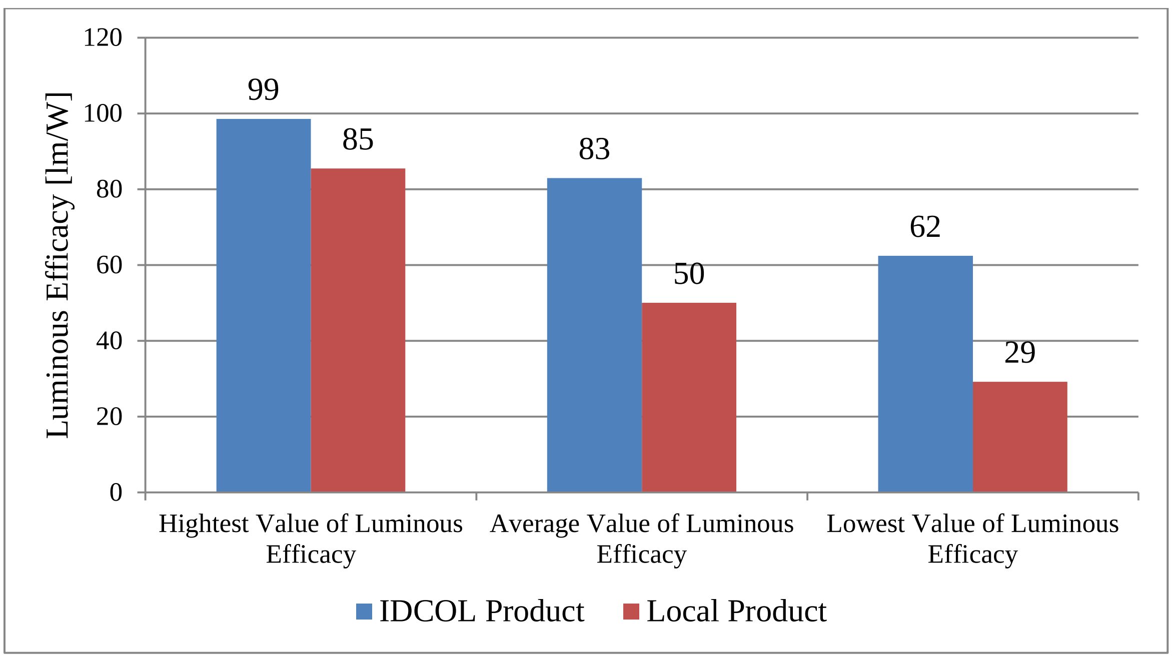


Figure 36. Comparison of luminous efficacy highest, average, and lowest values between IDCOL-approved and local-market LEDs.

Figure 36 presents a comparison between luminous efficacy values for IDCOL-approved and local-market LED products. The highest, average, and lowest values for both sets of products are included.

A simple two-sample t-test was used to determine if there is a statistically significant difference between IDCOL-approved and local-market LED products. The first step was to calculate average and standard deviation values for all four key performance metrics. Before using the t-test, a null hypothesis was generated. According to the null hypothesis there was no difference in the population mean values between the data sets. A two tail, t-test was performed for this analysis. For IDCOL-approved lamps there were values for 13 different products, and for local-market lamps there were values for 19 different products. Therefore, the data sets were unequal, unpaired, and independent of each other. The p value was the outcome of the t-test which indicated if the null hypothesis was true or false. In this analysis a 95% confidence level was considered, meaning that for any p value less than 0.05 the null hypothesis would be rejected. Table 8 includes p values for the total lumen output, lumen efficacy, CRI, and CCT. The respective p values were 0.65, <0.001, 0.67, and 0.48. Since the p values for lumen output, CRI, and CCT were higher than 0.05 for these three performance metrics the null hypothesis of no difference was therefore not rejected. In other words, the analysis did not support the conclusion that there was a difference between IDCOL-approved and local-market LED products for these performance metrics. For luminous efficacy the p value was found to be less than 0.001. This value is far lower than the critical value of p, and the null hypothesis of no difference was therefore rejected for luminous efficacy. This means that, for luminous efficacy, there was a statistically significant difference between the IDCOL-approved and local-market LEDs with the IDCOL products exhibiting higher luminous efficacy.

Table 8. Results for simple t-tests to determine if there were verifiable differences in performance between IDCOL-approved and local-market LEDs.

Performance Metric	Average Value		Std. Dev.		P Value
	IDCOL	Local	IDCOL	Local	
Total Lumen Output	259	247	27	109	0.65
Luminous Efficacy	83	50	12	14	<0.001
CRI	74	75	4	4	0.67
CCT	6518	6776	597	1378	0.48

My goals with respect to variability were (a) to determine the degree of variability within products that had a sample size of three and (b) to determine the degree of variability among products within two main product categories (i.e. IDCOL vs. local market). The variability associated with LED lamp performance was calculated in several different ways. First the variability between product models was calculated for both IDCOL-approved and local-market LED lamps. Then all IDCOL-approved products with a sample size of three were averaged to generate a single value for each product. Thus, there were values for 13 different models of IDCOL-approved products. Then the variability within models was also calculated.

A similar approach was used for local-market products. Before calculating coefficients of variation, sample mean values and sample standard deviation values were calculated for all the products. The calculated variability for the four key performance metrics included in this research, depicted here by the coefficient of variation (CV), ranged from minimal (<10%) to very high (>40%). A comparison among all products with a sample size of three revealed which models had the greatest levels of variability and which models had the least. The four key performance metrics were total lumen output, luminous efficacy, color rendering index (CRI), and correlated color temperature (CCT). For total lumen output, models LO and IA respectively had highest and lowest CV values. Model IC and IM, respectively, had the highest and lowest CV values for luminous efficacy. In the case of CRI, model IC had the highest CV value. There were two models that had the lowest values for CRI, namely the model IA and IH products. For CCT, model LO and IA respectively had the highest and lowest CV values. From Table 9, it is evident that the greatest level of variability was found for luminous efficacy values and the lowest levels of variability were associated with CRI.

Table 9. Mean, standard deviation, and coefficient of variation (CV) results for the IDCOL-approved LED models. The number of product models considered is indicated in column “A”.

Performance Metric	All IDCOL LEDs			
	A	Mean	Std. Dev.	CV
Total lumen output [lm]	13	259	27	10.4%
Luminous Efficacy (lm/W)	13	83	12	14.4%
CRI [-]	13	74	4	5.0%
CCT [K]	13	6518	597	9.2%

Table 9, above, represented variability within models for all IDCOL-approved products. From Table 10, it is evident that variability values for most of the key performance metrics for local-market LED lamps were higher than for IDCOL-approved lamps.

Table 10. Mean, standard deviation, and coefficient of variation (CV) results for the local- market LED lamp models. The number of product models considered is indicated in column "A".

Performance Metric	All Local LEDs			
	A	Mean	Std. Dev.	CV
Total lumen output [lm]	19	247	109	43.9%
Luminous Efficacy (lm/W)	19	50	14	28.1%
CRI [-]	19	75	4	4.8%
CCT [K]	19	6776	1378	20.3%

Only the CV value for CRI for local-market lamps was approximately equal to the IDCOL-approved lamps and was very slightly smaller. For the other performance metrics, the CV values for the local-market lamps were approximately two to four times greater. Similar to IDCOL-approved lamps, the lowest value of variability for local-market lamps was found for CRI. The greatest variability was revealed for total lumen output values for local-market lamps.

Visual Screening

Visual screening includes an evaluation of the robustness of the product's workmanship along with information collection related to other product attributes. In the visual screening section, information about the manufacturers contact details, advertised product specifications, product functionality, and workmanship quality for the product are reported. The results of visual screening testing are presented in this section. The Lighting Global quality assurance program follows a standard matrix to categorize samples and analyze results of visual screening testing. For this laboratory testing, a similar approach is used in which the products were determined to fall into three different categories: good, adequate, or poor, with regard to each visual screening metric. The number of product deficiencies and an assessment of the internal workmanship quality were two key factors for this evaluation. However, the number of allowable failures/deficiencies was modified for this analysis because the sample size for the visual screening analysis of lights from the Bangladesh market (n = 1) is smaller than the sample size for evaluation of pico-solar products tested under the Lighting Global program (n = 6).

Under Lighting Global's standard approach, if zero to two deficiencies are found across all six inspected samples, the sample is considered 'good.' If three to four deficiencies are noted, then the sample is rated as 'adequate.' And if more than four deficiencies are identified, the sample is categorized as 'poor.' In the case of the Bangladesh lamp testing, the evaluation criteria were modified for the visual screening test result analysis to account for the lower sample size and the fact that fewer visual screening metrics were included due to differences in the products. Table 11 provides a summary of the evaluation matrix that was used for this analysis.

Table 11. Matrix of categorization for visual screening both IDCOL-approved and local-market LEDs.

Matrix of Categorization	
Number of Deficiencies	Category
0	Good
1-2	Adequate
>2	Poor

The results from the visual screening evaluation are summarized in Tables 12 and 13.

Table 12. Numeric results for the visual screening analysis for IDCOL-approved and local-market LED lamps in Bangladesh.

Number of products that achieved each level of workmanship				
Type of the LED	Total Number of Product Models	Good	Adequate	Poor
IDCOL	13	12	1	0
Local	19	12	4	3

Table 13. Results for the visual screening analysis for IDCOL-approved and local-market LED lamps in Bangladesh.

Percentage of products that achieved each level of workmanship				
Type of the LED	Total Number of Product Models	Good	Adequate	Poor
IDCOL	13	92%	8%	0%
Local	19	63%	21%	16%

Table 12 indicates that, out of 13 different IDCOL-approved LED lamps, 12 were rated as having ‘good’ workmanship and one product was rated as having ‘adequate’ workmanship. Out of the 19 different local-market LED lamps, only 12 were rated as having ‘good’ workmanship, while four were rated as ‘adequate’ and three were rated as ‘poor’. Table 13 presents the same results in percentage form. These results provide a clear indication that local vendors need to work hard to improve the quality and workmanship of their products. A detailed summary of the visual screening results is included in Tables D-1 and D-2 of Appendix D.

Light Distribution

In the light distribution section, results for usable area, average lux, and full width half-maximum horizontal and vertical angle are reported. In addition to the measured values for the respective metrics, results are also presented that are related to average usable area and variance for IDCOL-approved and local-market LED lamps. Usable area is defined as the area upon which the lamps luminous flux is greater than 50 lux, and the maximum size of the usable area could be 1.2 square meters. Table 14 represents the average usable area, variance, and percentage of products with above 0.2 square meters of usable area for IDCOL-approved and local-market LED lamps. The 0.2 square meters of usable area (i.e., 45cm by 45cm) is the threshold value for the lamps to be useful for desk space.

Table 14. Average usable area, variance, and percentage of products with a usable area above 0.2- meter squares for IDCOL vs. local LED lamps.

	Average Usable Area (m^2)	Variance, S^2 (m^4)	Percentage of Products with Usable Area >0.2 m^2
IDCOL	0.83	0.041	100%
Local	0.64	0.188	79%

Figures 37 and 38 represent the usable area (>50 lux) on a work surface that is 0.75 meters away from the lamp for IDCOL-approved and local-market LED lamps, respectively.

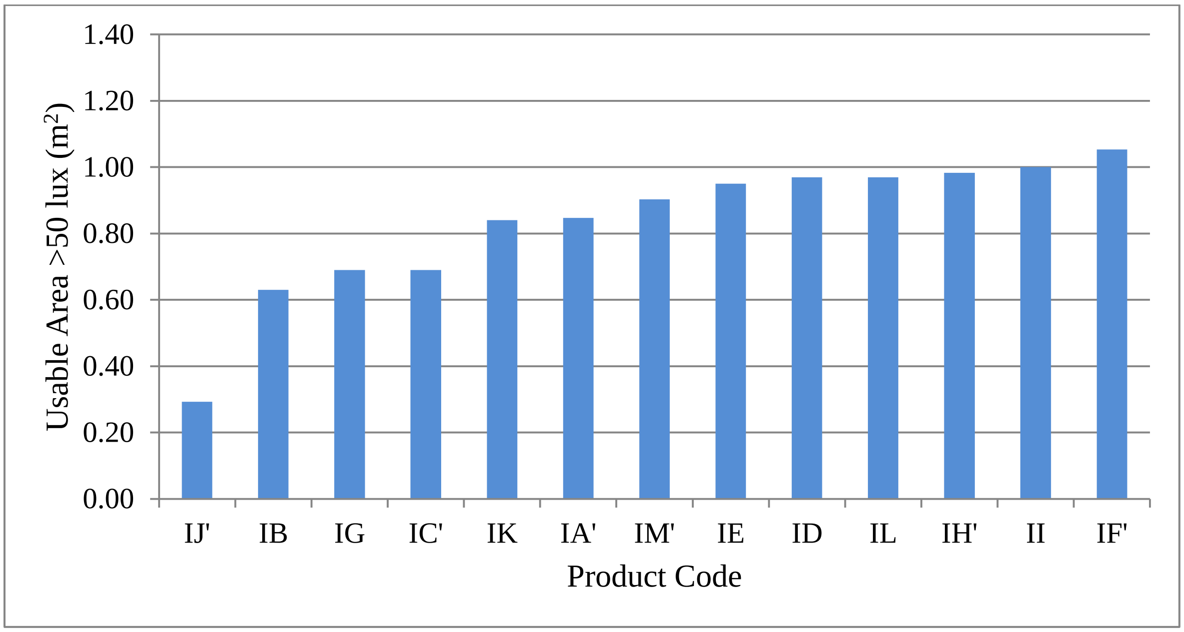


Figure 37. Usable area (>50 lux) on a work surface at a distance of 0.75 meters for IDCOL-approved LED lamps.

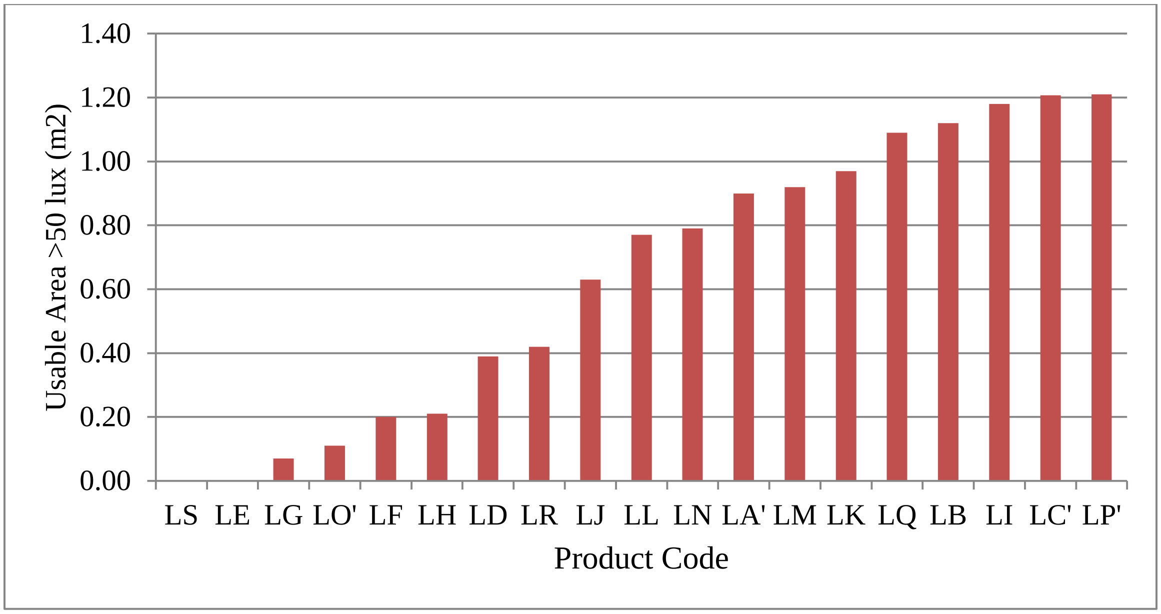


Figure 38. Usable area (>50 lux) on a work surface at a distance of 0.75 meters for local-market LED lamps.

From Figures 37 and 38, it is evident that the local-market LED lamps showed greater levels of variability with usable area than the IDCOL-approved lamps. Two of the local lamps did not produce a large enough surface illuminance area to be considered usable. On the other hand, the surface illuminance results for IDCOL-approved lamps showed more consistency. This means that IDCOL-approved lamps are more likely to perform reliably for task lighting applications for conditions similar to those specified in the test procedure. Two of the local-market lamps produced the maximum usable area of 1.2 square meters. A detailed summary of all measured results is included in Tables D-1 and D-2 of Appendix D. Figures 39 and 40 represent the average illuminance (in lux) that falls at each point on the 1m X 1m grid for IDCOL-approved and local-market LED lamps, respectively. The results presented in the figures provide clear evidence that the IDCOL-approved LEDs had higher illuminance values that the local-market LEDs.

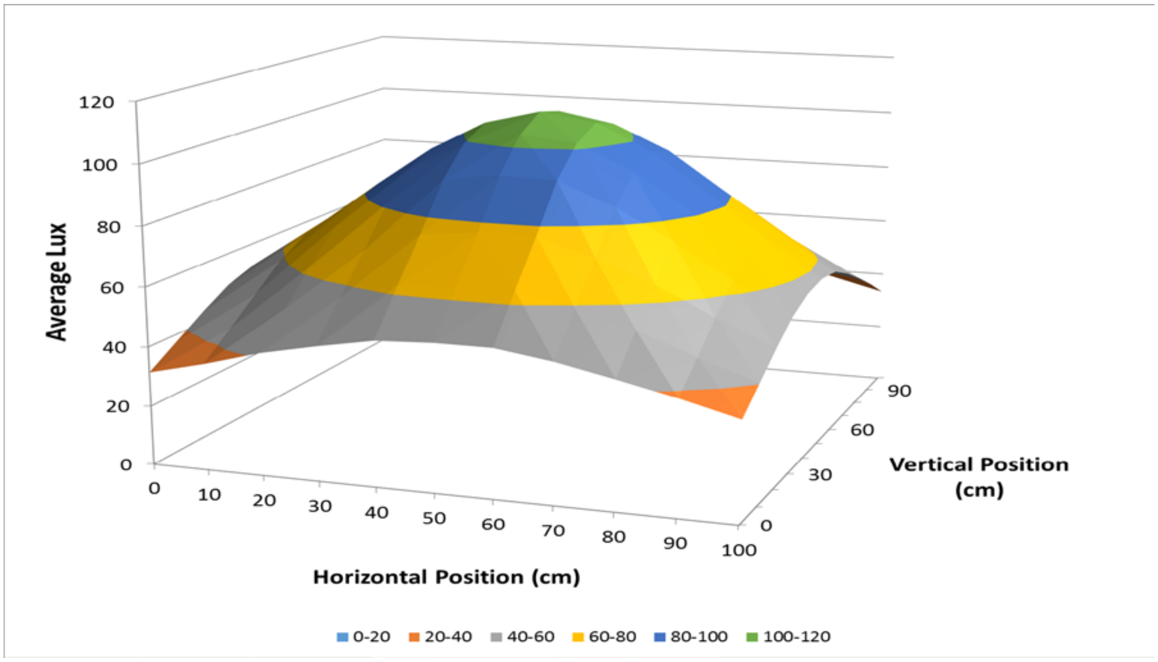


Figure 39. Surface plot of the average illumance on a plane that is 0.75 meters away from the light source for IDCOL-approved LED lamps.

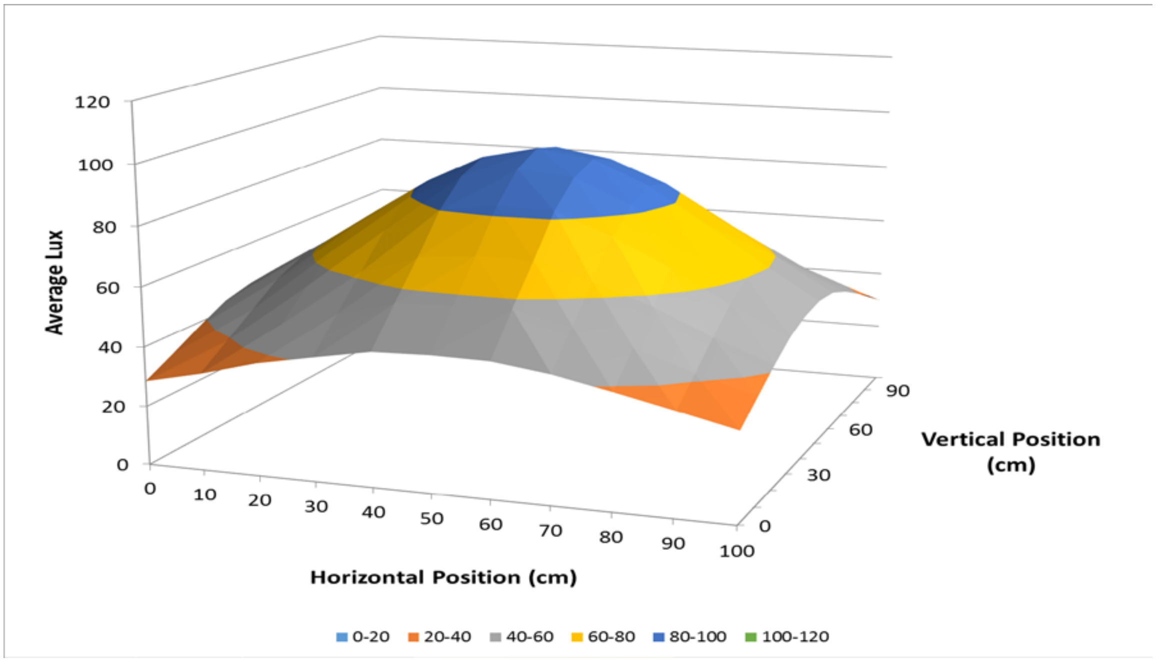


Figure 40. Surface plot of the average illumance on a plane that is 0.75 meters away from the light source for local-market LED lamps.

The full width half-maximum (FWHM) is a measure of the angle in which half of the total illuminance is attained in a plane that is directly perpendicular to the lamp. Two FWHM values were obtained for every lamp: One for the lamp's horizontal angle and one for vertical. In general, the orientation of the bulbs does not affect the FWHM because of their relatively uniform distribution of light. On the other hand, the tube lights demonstrate their directionality by having different FWHM angle values for their horizontal and vertical measurements. Figures 41 and 42 represent the FWHM measurements for IDCOL-approved and local-market LED lamps, respectively. This will help to differentiate between the LED tube lights and bulbs.

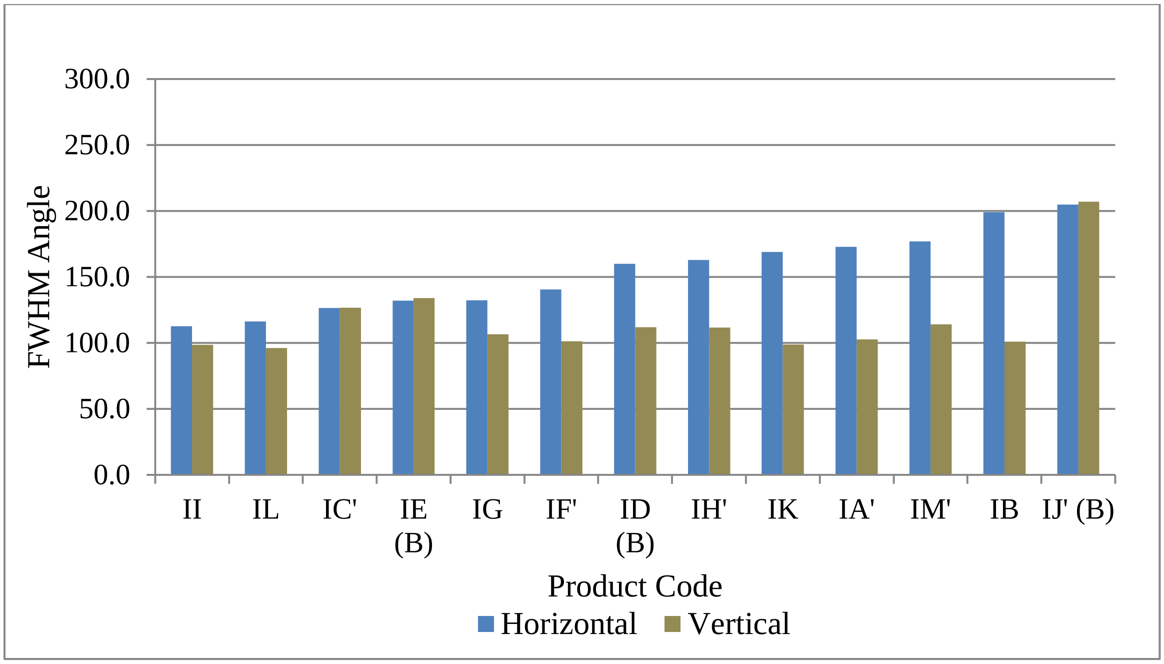


Figure 41. FWHM angle measures for horizontal and vertical planes for IDCOL-approved LED lamps. LED bulbs are labeled with a (B).

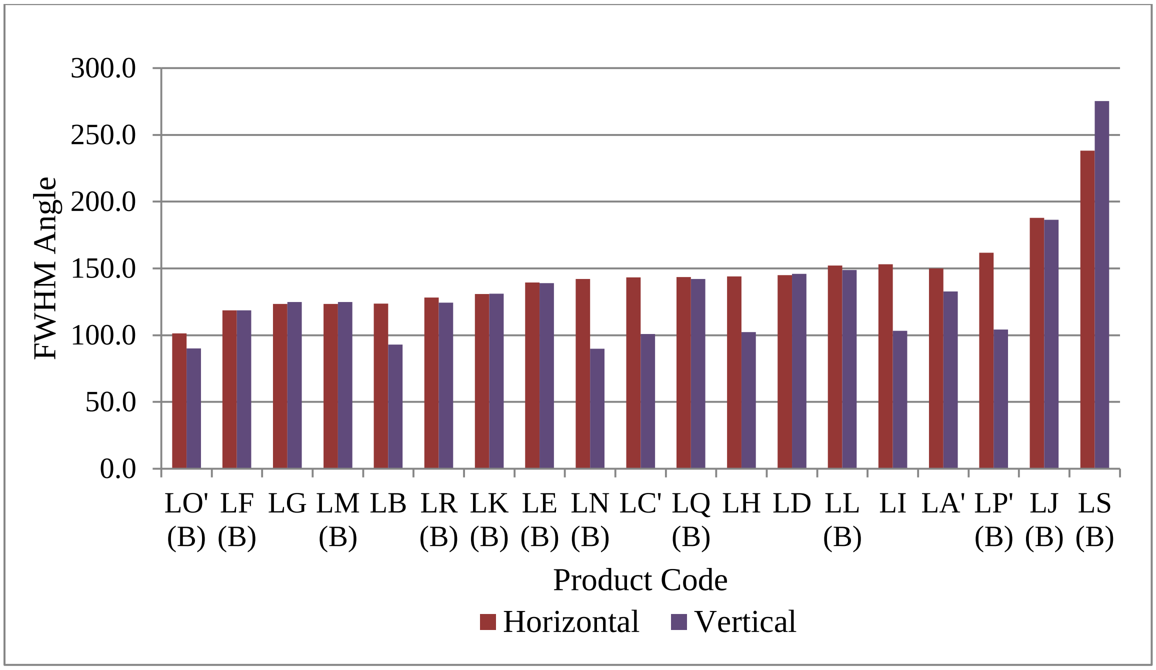


Figure 42. FWHM angle measurements for horizontal and vertical planes for local-market LED lamps. LED bulbs are labeled with a (B).

Performance Analysis of IDCOL vs. Local LED Lamps

As a final comparison of the IDCOL-approved and local-market LED lamps, this section includes an analysis of the level of service that is provided to SHS end users by the average lamp from each of the two types of SHS product suppliers. To make this comparison, I make calculations to determine the number of lumen-hours of lighting service that could be delivered per day using the average IDCOL-approved and the average local-market LED lamps, respectively. The result of this analysis highlights the benefits of high lumen efficacy for lamps used in off-grid solar applications. To make the analysis, I used a typical solar home system with a 30 W solar module operating in average conditions in Bangladesh as the baseline. According to my calculations, which I explain below, this system can generate about 3,400 lumen-hours of lighting services per day using the average IDCOL-approved lamp tested in this study or about 2,100 lumen-hours of lighting service per day using the average local-market LED lamp. This analysis shows the benefits of high lumen efficacy lamps, as a household would receive about 66% more lighting service per day in terms of lumen hours by using IDCOL-approved LEDs rather than those from the local market.

The performance between IDCOL-approved and local-market LED lamps for Bangladesh solar market was compared. To perform this analysis, it was necessary to make informed assumptions regarding values for the available solar insolation, solar PV module rating, efficiency losses for the SHS, the number of LED lights used, etc. Average lumen output and efficacy values were obtained from lab testing. Solar insolation referred to the amount of solar energy that reached the earth surface per unit area for the site. Bangladesh has an average annual solar insolation value of about 4.5kWh/m^2/day, and I used this value in the calculation. The next step is to calculate the amount of energy generated by a 30 Wp solar module given the conditions of an "average" day. If the solar module were able to utilize 100% of the available solar resource effectively, the panel would produce about 30Wp X 4.5 hours = 135Wh/day. In real life, it would not be possible to achieve this level of resource utilization due a variety of factors. There are efficiency losses related to module temperature, the angle of the module to the sun, soiling and aging of the modules, battery storage, resistance in wires and connectors, and others. The total loss factor of the system could reach up to 40% or more. Therefore, in real conditions only 55% to 75% of the electricity generated by the modules is typically available for use by lamps and other appliances (Intel, 2011). For this analysis, I assumed that 60% of the generated solar energy could be utilized effectively by end users in their lamps and appliances. As mentioned above, ideally a 30Wp panel would produce 135 watt-hours per day, but in reality it might only produce 135Wh X 60% or about 81Wh per day.

Lumen-hour Calculation for IDCOL-approved LED Lamps

The average total lumen output and luminous efficacy values for all IDCOL-approved products were, respectively, 259 lm and 83 lm/W. The number of hours of daily lighting service was calculated using these parameters and the analysis from the prior section. The first step was to divide the average total lumen output by the average luminous efficacy. For the average IDCOL-approved product, the result was 259 lm divided by 83 lm/W or 3.1W. Therefore, available hours of lighting per day from a 30 W solar system would be 81Wh divided by 3.1 W, or 26 hours. Assuming that only 50% of the available energy for the solar system was used for lighting (with the balance being used for other appliances), the available hours of lighting per day would be 26 hours X 50% or about 13 hours. If I assume that three LED lamps were used in the 30 W solar system and that their use is divided evenly, this results in about 4.3 hours of use per day for each light. Given an average light output of 259 lumens for each lamp, each single LED lamp would provide a level of daily lighting service equal to 259 lm times 4.3 hours or about 1,120 lm-hrs. As a result, for all three LED lamps, the overall average daily lighting service for the system would be 1,120 lm-hrs per lamp times three lamps or, to two significant figures, about 3,400 lm-hrs.

Lumen-hour Calculation for Local LEDs

The same analysis was performed to calculate the level of daily energy service for local-market LEDs. The average total lumen output and luminous efficacy values for all local-market products were, respectively, 247 lm and 50 lm/W. As noted previously, the average total lumen output value for local-market products was similar to those for the IDCOL-approved products, but there was a big difference between the average luminous efficacy values. As before, the calculation starts by dividing the average total lumen output for a lamp (247 lumens) by the average luminous efficacy (50 lm/W) for a result of 4.9 W. Therefore, available hours of lighting per day would be 81 Wh divided by 4.9 W or 16.4 hours. Again, assuming that only 50% of the available energy was used for lighting, the average number of hours of lighting per day would be 16.4 hours times 50%, or about 8.2 hours. If this light is divided evenly between three lamps, this results in about 2.7 hours of lighting per lamp per day. Assuming an average light output of 247 lumens for each lamp, each LED lamp would provide a level of daily service equal to 247 lm times 2.7 hours or about 675 lm-hrs. As a result, for all three LED lamps, the overall average daily lighting service for the system would be 675 lm-hrs per lamp times three lamps or, to two significant figures, about 2,100 lm-hrs.

DISCUSSION

The main objective of this research is to evaluate and compare the quality of the LED lamps that are currently available in Bangladesh solar market. This research provides information to market stakeholders about the market presence of LED lighting products in PO branch offices and shops in different divisions of Bangladesh. It also gives an idea of the current market scenario with respect to product preference, product quality, product ratings, and shop/PO branch office characteristics. Partner organizations offer a three-year warranty to their customers for IDCOL-approved LED lamps. PO sales representatives replace all the faulty lamps that fail within the warranty period. This means that customers pay money for a lamp that provides service for at least three years.

The laboratory test results included in this report provide information about the quality of LED lamps available in the Bangladesh solar market. These test results are used to perform data analyses. The outcomes of the analyses enabled me to evaluate and compare the quality of the lamps. Due to the low quality of their products, most of the local-market shopkeepers do not provide any warranty for the LED lamps. According to the laboratory test results, IDCOL-approved LED lamps perform better than local-market lamps. This indicates a clear difference in quality between IDCOL-approved and local-market LED lamps. The prices of the IDCOL-approved lamps are much higher than local-market lamps. Local-market lamps have advantages including cheap price, easy accessibility, and diverse range of products. The local-market shopkeepers stock a variety of LED lamps.

The difference in the sample mean luminous efficacy between IDCOL-approved and local-market lamps is (83 – 50) lm/W or 33 lm/W (66% difference), while the mean difference in price is BDT (457 – 113) or BDT 344 (304% difference). Therefore, the quotient of mean difference in price per mean difference in luminous efficacy would be BDT (344/33) or BDT 10.4 per (lm/W). This value is very important as it indicates what customers are paying on average per unit of luminous efficacy for the IDCOL-approved lamps. But this calcuation does not capture the better-quality and reliability of the IDCOL-approved LED lamps.Therefore, the importance of the IDCOL-approved LEDs is not reflected fully by this particular metric. Customers do not have access to the laboratory test results on luminous efficacy, and they may overestimate the quality of the local lamps. This number indicates that the cost per unit of increase in luminous efficacy that is actually being paid by customers is probably lower than it would be if customers were well informed. This serves as a simple way to explain the benefits of better-informed customers.

Moreover, the results of this research can help IDCOL and its partner organizations to address important challenges related to product quality and market development. IDCOL has successfully developed the largest market in the world for household solar home systems. Nonetheless, their POs have faced some challenges in recent years, and sales have declined after peaking in 2013. The availability of lower cost, lower quality solar products and appliances in local markets is one factor that has contributed to a reduction in sales. The laboratory results for LED lights published in this report confirm that lights sold by IDCOL POs are of significantly higher quality than those are sold in local markets. Moreover, the test methods used in this study could be used by laboratories in Bangladesh to confirm lamp performance and to help ensure that Bangladesh solar home system users have access to good quality lights.

RECOMMENDATIONS

The results of the performance testing showed significant variations in quality and performance between IDCOL-approved and local-market lamps. These results represented the quality of the LEDs, and they indicate that IDCOL should test their approved products regularly to ensure the proper quality. As mentioned earlier, the quality of the IDCOL-approved products is generally better than the quality of the local-market products. In fact, the difference in quality between the IDCOL-approved products and the local-market product is substantial. Many of the local-market products exhibited rapid lumen depreciation, and their lumen efficacy was considerably lower. These are two key metrics of quality, and the differences are large. For this reason, it is very important for IDCOL to keep on improving the quality of the LEDs. On the other hand, the local vendors should also work to improve the quality of their products. Regular testing of the lamps will eventually contribute to overall development of LED technology.

The result of the fieldwork is an integral part of this research paper. It helped me to understand the common complaints of LED lamp users in Bangladesh. It also gave me the overview of the customer’s expectation from the LEDs. The feedback of the customers enables the manufacturers to be aware of issues they need to work on. These feedbacks also encourage manufactures to improve their product’s quality. The survey results helped me to identify main problems of the IDCOL-approved lamps, including

LEDs that dimmed and failed to operate properly. For local-market lamps, lack of information about customer expectations and complaints are the main concerns. The majority of the customers do not share any information about the problems they face with the shopkeepers. As a result, our survey results could not capture that information. A more in-depth field analysis of LED user complaints paired with communication of the results to manufactures, shopkeepers, and POs could be advantageous for this research.

The test results represent the performance of 32 different LED lamps collected from both POs and shopkeepers. These were the most commonly used LED lamps in the Bangladesh solar market at the time that they were collected. Nonetheless, there are many other models of LED lights that were not included in this study. A more comprehensive analysis covering a wider range of LED products would provide a more complete view of the quality of LED lamps in Bangladesh. In fact, with time the sales of the currently popular LED brands might drop or some new brands might enter the market. For this reason, new studies of the quality and performance of LED lamps will be needed in the future.

The cost of the IDCOL-approved LEDs is higher than the cost of the local-market ones. This is one of the main reasons why the customers tend to purchase the LEDs from the local market. Due to their superior quality and performance, the IDCOL-approved LED lamps are expected to last longer and provide higher levels of lighting service than those available through local-market channels. However, due to their higher price, the better quality lamps are losing market share to lower cost and lower quality lamps.

Creating awareness among customers about the difference in quality could be one feasible solution to this problem. Customers need to know about the benefits that they receive in the long run if they buy IDCOL-approved LEDs. IDCOL, along with the POs, should take initiative to reach the customers and spread the word. Laboratory test results can give IDCOL and its POs the facts that they need.

CONCLUSION

Both the laboratory based performance testing and fieldwork provided important information about the LED lamps available in the Bangladesh solar market. Based on PO sales representative and shopkeeper survey outcomes, it can be said that IDCOL-approved LEDs are clearly superior and their higher initial cost is a small issue relative to the increased benefit that they bring over the lifetime of system. The average price of the local-market products was BDT 113 ($1.44), which was considerably lower than the average price for IDCOL-approved lamps BDT 457 ($5.83). This difference in the average prices indicates that the price of the LEDs in the PO based markets is a lot higher than the local market based LEDs. The good reputation of the partner organizations can also influence the customers to buy the branded LEDs at a higher price. The durability of the LEDs would play a key role in case of economic feasibility analysis. Out of 13 different IDCOL-approved LED lamps, 12 were rated as having ‘good’ workmanship and one product was rated as having ‘adequate’ workmanship. Out of the 19 different local-market LED lamps, only 12 were rated as having ‘good’ workmanship, while four were rated as ‘adequate’ and three were rated as ‘poor’. Thus it is very evident that the IDCOL-approved LEDs are better made and are likely to be more durable than local-market LEDs.

This research work is useful to everyone related to the field of LED technology. My thesis work mainly discloses the difference in quality between IDCOL-approved and local-market LED lamps. This research identifies the problems associated with the quality of these lamps and also highlights importance of laboratory testing to maintain the standard quality of LED lamps. A performance analysis between IDCOL-approved and local-market LED shows the benefits of high lumen efficacy lamps, as a household would receive about 66% more lighting service per day in terms of lumen hours by using IDCOL-approved LEDs rather than those from the local market. LED lamps play a vital role in supporting the overall growth of SHS market. Therefore, maintaining good quality of lamps is crucial for successful growth of the SHS market. Low-quality lamps can impact sales growth and deter people from using the technology. The average luminous efficacy for IDCOL-approved and local-market lamps were, respectively, 83 (lm/W) and 50 (lm/W). The laboratory results for LED lamps confirm significantly higher level of quality for IDCOL-approved lamps relative to local-market lamps. The enforcement of a standard quality assurance program could protect the interests of low-income end users of LED lamps. My thesis work seeks to contribute to the growth of energy efficient off-grid lighting products in Bangladesh solar market and to add real value to the field of LED technology.

REFERENCES

Alstone, P., Radecsky, K., Jacobson, A., & Mills, E. (2014). *Field study methods and results from a market trial of LED lighting for night market vendors in rural Kenya.* Retrieved May 1, 2016, from http://users.humboldt.edu/arne/Alstone-etal-LED-Market-Trial-Kenya-LightEngineeering-2014.pdf

Akerlof, G. A. (1970). *The market for 'Lemons': quality uncertainty and the market mechanism.* Retrieved May 1, 2016, from https://www.iei.liu.se/nek/730g83/artiklar/1.328833/AkerlofMarketforLemons.pdf

Duke, R. D., Jacobson, A., & Kammen, D. M. (2002). *Photovoltaic module quality in the Kenyan solar home systems market.* Retrieved May 1, 2016, from http://users.humboldt.edu/arne/SHS_EnergyPolicy_2002.pdf

Haque, S. (2016, January 30). Personal communication in the context of an email interview. Relationship Manager, Infrastructure Development Company Limited (IDCOL)

Haldman, B., Porter, W.A., Ruppert, K. C., & Cantrell, R.A. (2008). *Energy efficient homes: Introduction to LED lighting.* Retrieved April 5, 2016, from https://edis.ifas.ufl.edu/pdffiles/FY/FY104900.pdf

Infrastructure Development Company Limited (2014a). *Solar home systems program*, Retrieved April 29, 2016, from http://idcol.org/home/solar

Infrastructure Development Company Limited (2014b). *Lending terms*, Retrieved April 29, 2016, from http://idcol.org/home/r_lending_terms

Infrastructure Development Company Limited (2014c). *Energy efficiency*, Retrieved April 30, 2016, from http://idcol.org/home/energy_e

Infrastructure Development Company Limited (2016). *Technical specifications for solar home system (SHS), R*etrieved April 29, 2016, from http://idcol.org/download/08fbec513b301cf441c9fabc85ac6e3f.pdf

Infrastructure Development Company Limited (n.d.). *Document checklist for approval of solar PV module and other appliances under IDCOL solar home system (SHS) program, R*etrieved May 1, 2016, from http://idcol.org/download/0c6e723675507a3e8ae943b427a871b5.pdf

International Electrotechnical Commission (2015). *Technical Specification 62257-12-1*. Retrieved April 30, 2016, from https://webstore.iec.ch/preview/info_iec62257-12-1%7Bed2.0%7Den.pdf

Intel (2011). *Solar power for PC deployments: Enabling ICT beyond the grid*, Retrieved April 29, 2016, from http://www.intel.com/Assets/PDF/casestudies/WA-324794.pdf

Islam, S.M.M. (2014, April 25). *IDCOL solar home system program.* Retrieved April 5, 2016, from https://www.esmap.org/sites/esmap.org/files/ESMAP_SAR_EAP_Renewable_Energy_Resource_Mapping_Islam.pdf

Karim, M.E. (2015, January 13). Personal communication in the context of an email interview. Head of Renewable Energy, Infrastructure Development Company Limited (IDCOL).

Khandker, S. R., Samad, H. A., Sadeque, Z. K. M., Asaduzzaman, M., Yunus, M., & Haque, A. K. E. (2014). *Surge in solar-powered homes: experience in off-grid rural Bangladesh.* Retrieved April 29, 2016, from https://openknowledge.worldbank.org/bitstream/handle/10986/20427/913490PUB097810B00PUBLIC00100802014.pdf?sequence=1

Lighting Global (2015). *Quality assurance for off-grid solar home systems: A comparison of strategies employed by lighting global and the Bangladesh IDCOL solar home system program.* World Bank Group. Retrieved May 3, 2016, from https://www.lightingglobal.org/comparison-of-the-lighting-global-and-idcol-quality-assurance-frameworks/

Lighting Global (2010). *LED lumen depreciation and lifetime*, Lighting Global Technical Note Issue 2, World Bank Group. Retrieved from https://www.lightingglobal.org/resources/technical-notes/

LEDKE Technology Co., Ltd. (2010). *Advantages and Disadvantages of LED.* Retrieved May 1, 2016, from http://www.ledke.com/news/Advantages-Disadvantages-LED.html

Luminanz Ltd (2011). *Disadvantages of using traditional LEDs*, Retrieved from http://www.luminanz.co.uk/tech_disadvantages.php

Marro, P. and, Bertsch N. (2015). *Making renewable energy a success in Bangladesh: Getting the business model right.* Retrieved April 5, 2016, from http://www.adb.org/sites/default/files/publication/177814/ban-making-renewable-energy-success.pdf

NEWAGE (2014). *Govt to promote LED bulbs.* Retrieved April 30, 2016, from http://newagebd.net/19879/govt-to-promote-led-bulbs/

Nielsen, K. (2014). *Color temperature and LED: understanding how to choose LED lamps for warm and cool applications.* Retrieved May 1, 2016, from http://solutions.borderstates.com/color-temperature-and-led-understanding-how-to-choose-led-lamps-for-warm-and-cool-applications

Phadke, A., Jacobson, A., Park, W. Y., Lee, G. R., Alstone, P., & Khare, A. (2015). *Powering a home with just 25 watts of solar PV: Super-efficient appliances can enable expanded off-grid energy service using small solar power systems.* Lawrence Berkeley Laboratory report number 175726. Retrieved May 2, 2016, from http://eetd.lbl.gov/sites/all/files/lbnl-175726.pdf

Rural Poverty Portal (2012). *Rural poverty in Bangladesh.* Retrieved April 30, 2016, from http://www.ruralpovertyportal.org/country/home/tags/bangladesh

Sadeque, Z., Rysankova, D., Elahi, R., & Soni, R. (2014). *Scaling up access to electricity: The case of Bangladesh.* Retrieved April 5, 2016, from https://beamexchange.org/uploads/filer_public/8e/e1/8ee18db2-99b6-46ae-a5ee-70764fb70b67/scalingup_electricity_bangladesh.pdf

Scoyk, D. V. (2010). *LED lighting: Is it time to change from fluorescent and incandescent light*?. Retrieved April 5, 2016, from http://www.superiorlight.com/LED%20White%20Paper%2010-3-11%20.pdf

Siegel, J. R. and Rahman, A. (2011). *The diffusion of off-grid solar photovoltaic technology in rural Bangladesh.* Retrieved May 1, 2016, from http://fletcher.tufts.edu/~/media/Fletcher/Microsites/CIERP/Publications/2011/SiegelRahman11SepSolarEnergy_Fsin.pdf

UNICEF (n.d.). *Bangladesh today.* Retrieved April 30, 2016, from http://www.unicef.org/bangladesh/overview_4840.htm

U.S. Department of Energy (2012). *Building technologies program solid-state lighting technology fact sheet*, Retrieved April 5, 2016, from http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf

U.S. Department of Energy (n.d.). *How energy-efficient light bulbs compare with traditional incandescents.* Retrieved April 30, 2016, from http://energy.gov/energysaver/how-energy-efficient-light-bulbs-compare-traditional-incandescents

U.S. Department of Energy (n.d.). *LED lighting.* Retrieved April 30, 2016, from http://energy.gov/energysaver/led-lighting

U.S. Department of Energy (n.d.). *Incandescent lighting.* Retrieved April 30, 2016, from http://energy.gov/energysaver/incandescent-lighting

Zobaer, M. A., & Sarkar, M. A. R. (2013). *Renewable energy for rural development in Bangladesh*. Retrieved April 30, 2016, from http://icmime ruet.ac.bd/2013/Contents/Technical%20Papers/Energy%20Technology/ET-13.pdf

APPENDIX A. PO SALES REPRESENTATIVE SURVEY

Off-Grid Lighting Research in Rural Bangladesh May 2015.

Surveyor Name(s)____________________________________

Date		**Town**	
PO Name			
Location			
GPS Point #		**Box #**	
Phone #			
PO Head Office Address			

Interviewee

Name	
Gen	***M*** [1] ***F*** [2]
Position	***Sales Representative*** [1] ***Manager*** [2] ***Other*** [3]

PO Name__________________ Surveyor Initials_______

Fill in each line completely for each product model of LED lamp that is sold by the ***PO***

	IDCOL	Price	About how many did you sell in the past 7 days?						
Code for data entry→			[1]	[2]	[3]	[4]	[5]	[6]	[7]
Product Brand / Model/Features **(Top selling one's should be mentioned first)**	IDCOL?	**Price (Taka)**	**0**	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**	**50+**

1.1 When did your company **first** start selling LED lighting products?

☐ 3 months ago [1] ☐ 6 months ago [2] ☐ 1 year ago [3]

☐ 1.5 years ago [4] ☐ 2 years ago [5] ☐ 3 years ago [6]

☐ 3- 6 years ago [7] ☐ 6+ years ago [8] ☐ Do not sell yet [9]

1.2 **What** are the main factors that **customers** consider when they purchase an LED lamp? Please indicate which factor is the most important one for the customers.

☐Price [1] ☐Durability [2] ☐Brightness [3] ☐Warranty [4]

☐Light color [5] ☐Brand of Product [6] ☐Brand of Product [7]

☐Other factors [8] If other, please indicate: ________________________

____

1.3 What are the **main problems** or **quality issues** that you or your **retailers** have experienced with the LED lighting products that you sell? (Mark all that apply)

☐LEDs become dim ☐LEDs fail to operate ☐Breakage from dropping

☐Other problems (please note below)

Other Problems experienced: ____

____

1.4 How does this compare to your experience of fluorescent lamps??

☐Better [1] ☐Worse [2] ☐Same [3] ☐No Idea [4]

1.5 Does your company offer any **credit** to **retailers** or **guarantees** on products?

☐Credit Offered [1] ☐Guarantee Offered [2] ☐Both Offered [3] ☐None Offered [4]

1.6 If a warranty is offered on the LED lights that are sold, what are the warranty terms? (i.e. what is the length of the warranty and what the main conditions?)

Warranty length (months): _______________

Other warranty terms: ____

APPENDIX B. SHOPKEEPER SURVEY

Off-Grid Lighting Research in Rural Bangladesh May 2015.

Surveyor Name(s)______________________________________

Date		**Town**	
Shop Name			
Location			
GPS Point #		**Box #**	
Phone #			
Shop Type	Electrical/ [1] GenShop [2] Supermarket [3] Hardware [4] Solar [5] Electronics		
	MarketStall [6] Hawker [7] PO Agent [8] OTHER [9]		
# Employees	**1-2** [1] **3-5** [2] **6-10** [3] **11+** [4]		

Interviewee

Name	
Gen	***M*** [1] ***F*** [2]
Position	***Owner*** [1] ***Worker*** [2] ***Other*** [3]

Fill in each line completely for each product model of LED lamp that is sold by the shop or entrepreneur

	IDCOL	Price	About how many did you sell in the past 7 days?						
Code for data entry→			[1]	[2]	[3]	[4]	[5]	[6]	[7]
Product Brand / Model **(and features)**	IDCOL?	**Price (Taka)**	**0**	**1-5**	**6-10**	**11-20**	**21-30**	**31-40**	**40+**

1.1 Is this a normal week for sales?

☐Low [1] ☐Normal [2] ☐High [3]

1.2 When did the shop **first** start selling LED lighting products?

☐ 3 months ago☐[1] ☐6 months ago [2] ☐1 year ago [3]

☐1.5 years ago [4] ☐ 2 years ago [5] ☐ 3 years ago [6]

☐ 3- 6 years ago [7] ☐ 6+ years ago [8] ☐ Do not sell yet [9]

1.3 **What** are the main factors that people consider when they purchase an LED lamp? Please indicate which factor is the most important one for your customers.

☐Price [1] ☐Durability [2] ☐Brightness [3] ☐Warranty [4]

☐Light color [5] ☐Brand of Product [6] ☐Brand of Product [7]

☐Other factors [8] If other, please indicate: ______________________

____

1.4 What are the **main problems** or **quality issues** that you or your customers have experienced with the LED lighting products that you sell? (Mark all that apply and then mark the most frequent problem.)

☐LEDs become dim ☐LEDs fail to operate ☐Breakage from dropping

☐Failure of a switch or connector ☐Other problems (please note below)

Other Problems experienced: _______________________________________

____

1.5 Do you mainly sell products on a **retail** basis or a **wholesale** basis?

☐Retail [1] ☐Wholesale [2] ☐Both [3]

1.6 Does your shop offer any **credit** to customers or **warranties** on products?

☐Credit Offered [1] ☐Warranty Offered [2] ☐Both Offered [3] ☐None Offered [4]

1.7 If a warranty is offered on the LED lights that are sold, what are the warranty terms? (i.e. what is the length of the warranty and what the main conditions?)

Warranty length (months): _______________

Other warranty terms: ____

APPENDIX C. DETAIL OF LIGHT OUTPUT RESULTS

Table C-1: Detailed values for all the key performance metrics for IDCOL-approved LED lamps. The averaged product results are noted by adding a prime (') symbol to the respective product codes.

Product Code	Total lumen output [lm]	Voltage at product [V}	Current at product [A]	Luminous Efficacy (lm/W)	CRI [-]	CCT [K]
IA'	278	12.30	0.2402	94	75	6221
IB	253	12.30	0.2246	92	75	6661
IC'	259	12.30	0.3378	71	78	6025
ID	231	12.30	0.24	79	71	6339
IE	272	12.30	0.35	62	75	6769
IF'	293	12.30	0.2417	99	83	5973
IG	203	12.30	0.2558	64	71	6722
IH'	276	12.30	0.2432	92	75	6220
IJ'	291	12.30	0.2494	95	74	6723
II	239	12.30	0.2465	79	73	6278
IM'	275	12.30	0.2658	84	74	6045
IK	273	12.30	0.2461	90	74	6485
IL	228	12.30	0.2392	78	68	8271

Table C-2: Detailed values for all the key performance metrics for local-market LED lamps. The averaged product results are noted by adding a prime (') symbol to the respective product codes.

Product Code	Total lumen output [lm]	Voltage at product [V}	Current at product [A]	Luminous Efficacy (lm/W)	CRI [-]	CCT [K]
LA'	262	12.30	0.6796	33	73	7006
LB	316	12.30	0.37	70	70	6383
LC'	417	12.30	0.7741	44	73	7202
LD	210	12.30	0.43	40	78	6017
LE	102	12.30	0.18	46	76	5539
LF	132	12.30	0.27	40	75	6376
LO'	105	12.30	0.2428	35	72	7039
LP'	459	12.30	0.8797	42	75	6706
LQ	327	12.30	0.53	51	74	6557
LR	179	12.30	0.26	57	79	6535
LS	145	12.30	0.39	30	87	6852
LG	252	12.30	0.33	63	76	6040
LH	143	12.30	0.18	65	72	6393
LI	385	12.30	0.54	58	72	6092
LJ	334	12.30	0.32	85	76	6211
LK	264	12.30	0.48	44	74	6911
LL	259	12.30	0.36	58	73	6091
LM	285	12.30	0.49	48	74	6607
LN	119	12.30	0.23	42	77	12192

Table C-3: Detailed results of mean, standard deviation, and coefficient of variation (CV).

Product Code	Mean	Std. Deviation	CV
IA	278	1.1826	0.4%
	94	1.6709	1.8%
	75	0.1528	0.2%
	6221	23.671	0.4%
IC	259	9.9641	3.8%
	71	25.167	35.6%
	78	6.4423	8.2%
	6025	184.08	3.1%
IF	293	4.5015	1.5%
	99	4.2755	4.3%
	83	0.5	0.6%
	5973	151.24	2.5%
IH	276	3.5187	1.3%
	92	1.2255	1.3%
	75	0.17321	0.2%
	6220	112.96	1.8%
IJ	291	1.6655	0.6%
	95	1.4830	1.6%
	74	0.45092	0.6%
	6723	211.02	3.1%
IM	275	17.783	6.5%
	84	0.53593	0.6%
	74	1.6258	2.2%
	6045	37.643	0.6%
LA	262	29.386	11.2%
	33	8.1733	24.8%
	73	1.6703	2.3%
	7006	693.13	9.9%
LC	417	33.627	8.1%
	44	5.7342	13.0%
	73	0.79373	1.1%
	7202	87.306	1.2%
LO	105	17.202	16.4%
	35	3.1711	9.1%
	72	0.20817	0.3%
	7039	1120.4	15.9%

Table C-3 continued

Product Code	Mean	Std. Deviation	CV
LP	459	4.5606	1.0%
	42	1.6122	3.8%
	75	0.43589	0.6%
	6706	187.74	2.8%

APPENDIX D. DETAIL OF LUMEN MAINTENANCE, LIGHT DISTRIBUTION, and VISUAL SCREENING RESULTS

Table D-1: Percentage of initial lumen output at 2000 hour, usable working surface, horizontal FWHW angel, vertical FWHM angel, and categories for IDCOL-approved LED lamps.

	Lumen Maintenance	Light Distribution			Visual Screening
Product Code	Percent of initial lumen output at 2000 h [%]	Usable working surface (>50 lx) [m2]	Horizontal FWHM Angel [degrees]	Vertical FWHM Angle [degrees]	Category
IA'	101	0.85	173	103	Good
IB	101	0.63	199	101	Good
IC'	100	0.69	126	127	Good
ID	102	0.97	160	112	Good
IE	62	0.95	132	134	Good
IF'	97	1.05	141	101	Good
IG	93	0.69	132	107	Good
IH'	100	0.98	163	112	Good
IJ'	102	0.29	205	207	Good
II	103	1	113	99	Good
IM'	103	0.9	177	114	Good
IK	99	0.84	169	99	Adequate
IL	87	0.97	116	96	Good

Table D-2: Percentage of initial lumen output at 2000 hour, usable working surface, horizontal FWHW angel, vertical FWHM angel, and categories for local-market LED lamps.

	Lumen Maintenance	Light Distribution			Visual Screening
Product Code	Percent of initial lumen output at 2000 h [%]	Useable working surface (>50 lx) [m2]	Horizontal FWHM Angel [degrees]	Vertical FWHM Angle [degrees]	Category
LA'	61	0.9	154	103	Poor
LB	106	1.12	124	93	Poor
LC'	85	1.21	143	101	Good
LD	0	0.39	145	146	Good
LE	84	0	139	139	Good
LF	98	0.2	119	119	Adequate
LO'	37	0.1	101	90	Good
LP'	32	1.21	162	104	Good
LQ	87	1.09	144	142	Good
LR	93	0.42	128	124	Good
LS	0	0	238	275	Poor
LG	9	0.07	123	125	Good
LH	20	0.21	144	102	Adequate
LI	0	1.18	153	103	Good
LJ	104	0.63	188	186	Good
LK	78	0.97	131	131	Adequate
LL	95	0.77	152	149	Good
LM	92	0.92	123	125	Good
LN	86	0.79	142	90	Adequate

APPENDIX E. PHOTO GALLERY

Figure E-1: Asif Hassan conducting survey with PO sales representatives. On the left is the Bright Green Energy Foundation (BGEF) branch office in Sylhet (Photo credit: BGEF office staff), and on the right is the Thengamara Mohila Sabuj Sangha (TMSS) branch office in Manikganj (Photo credit: TMSS office staff).

Figure E-2: On the left is the Grameen Shakti (GS) branch office in Manikganj (Photo credit: Asif Hassan), and on the right is the Grameen Shakti (GS) divisional manager's office in Natore (Photo credit: GS office staff).

Figure E-3: On the left is the storage room at Grameen Shakti (GS) branch office in Manikganj, and on the right is the testing facility at Grameen Shakti (GS) divisional manager's office in Natore (Photo credit: Asif Hassan). In this test facility, voltage and current of the LED lamps are measured.

Figure E-4: On the left is the inside of the Sundarban Square Super Market in Nababpur, Dhaka, and on the right is the outside of the market. (Photo credit: Asif Hassan).

Figure E-5: On the left is a large solar shop in Lal Bazar, Sylhet, and on the right is a large solar and electronics market in Lal Bazar, Sylhet (Photo credit: Asif Hassan).

Figure E-6: On the left is the storage room at Patakuri branch office in B.Baria, and on the right is the storage room at Thengamara Mohila Sabuj Sangha (TMSS) branch office in Manikganj (Photo credit: Asif Hassan).

Figure E-7: On the left is the sample LED tube light used for laboratory tests, and on the right is the sample LED bulb used for laboratory tests (Photo credit: Jeffrey Mosbacher).

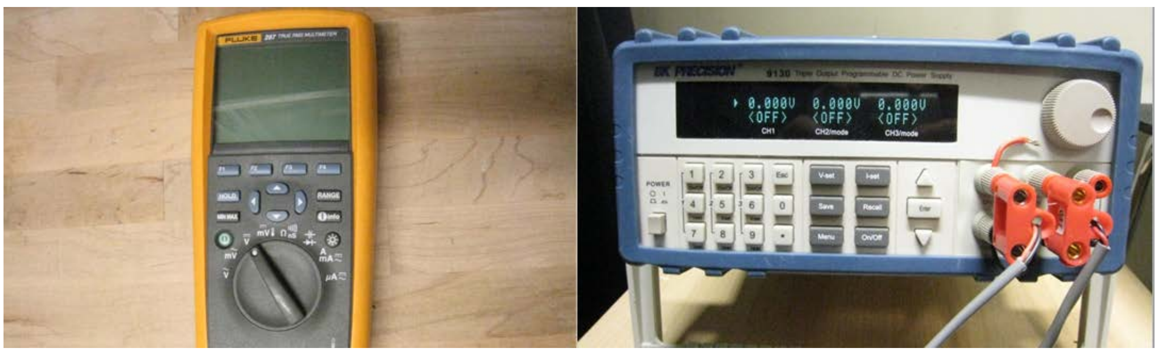


Figure E-8: On the left is the multi-meter used for laboratory tests, and on the right is the programmable DC power supply used for laboratory tests (Photo credit: Jeffrey Mosbacher).