METHODS AND ANALYSIS FOR ESTIMATING THE DAILY OPERATING TIME OF SOLAR CHARGED OFF-GRID LIGHTING PRODUCTS

By

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ABSTRACT

METHODS AND ANALYSIS FOR ESTIMATING THE DAILY OPERATING TIME OF SOLAR CHARGED OFF-GRID LIGHTING PRODUCTS

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Access to clean and affordable lighting services is an important part of addressing issues of equality, development and the environment. Flame based lighting, which is the primary source of light for over a billion people worldwide, is expensive, hazardous for users, and environmentally damaging. In the last decade, off-grid lighting technologies like light emitting diodes (LED) and compact fluorescent lights (CFL) have emerged as a bridge between the traditional flame-based lighting and access to the electric grid. This study includes an evaluation of current empirical and analytical methods for estimating the daily operating time of solar charged off-grid lighting products. The study also explores low cost measures to improve the accuracy of these methods. Experimental tests conducted with a variety of off-grid solar charged lighting products have shown that the method developed by Fraunhofer ISE for estimating the daily operating time of the products tested is imprecise. Revisions to the Fraunhofer ISE method proposed in this study and the abbreviated version of the PV GAP method (12 hour cycle) resulted in improved estimates of daily operating time. However, neither of these methods provides accurate results for some products but inaccurate results for all product types. Future

efforts should focus on combining elements of these methods to create an accurate, low cost approach for evaluating daily operating time for off-grid lighting products. This study has also identified a framework to incorporate accessory charging features of lighting products (e.g. mobile phone charging) into an estimate of daily operating time. Future efforts will be directed at validating this new framework for calculating daily operating time.

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1 INTRODUCTION

According to the International Energy Agency (IEA), almost 1.3 billion people on the planet have no access to the electric grid (IEA, 2010). For people that are not connected to the electric grid, the main sources of lighting are flame-based lighting devices like kerosene lamps, oil lamps and candles. These traditional devices for lighting are a source of indoor air pollution and greenhouse gas emissions. More than one million people a year die from chronic obstructive respiratory disease that develops due to exposure to such indoor air pollution (World Health Organization, 2011). In addition to environmental and health concerns, the quality of lighting services offered by these traditional technologies is often poor. Adequate light has been socially related to literacy, income generating activities and improved security (Mills, 2005). Therefore, access to clean and affordable lighting services is an important part of addressing issues of equality, development and the environment.

Off-grid lighting technologies like light emitting diodes (LED) and compact fluorescent lights (CFL) have emerged as a bridge between the traditional flame based lighting and access to the electric grid. These lighting technologies have gained prominence because they are cost effective, robust and use small amounts of energy. With the emergence of a large market for these technologies in the last decade, there have been parallel efforts to develop a quality assurance framework for these products. The main idea of these efforts is to help sustain a healthy market for cost effective and good quality off-grid lighting products for low-income households.

Lighting Africa is a joint International Finance Corporation (IFC) and World Bank program that is working towards mobilizing the private sector in order to help build a sustainable and healthy off-grid lighting market. One of the outcomes of the Lighting Africa program is the development of the Lighting Africa Quality Test Method (LAQTM), which includes a complete set of test procedures for evaluating various aspects of an off-grid lighting product.

This study will present the methods and analysis for estimating the daily operating time for solar charged off-grid lighting products. Daily operating time is one of the performance metrics for evaluating off-grid lighting product in the LAQTM. This is an important parameter since it gives an indication of how a product may perform on a daily basis in the field. The study will include evaluating current empirical and analytical methods for estimating the daily operating time of an off-grid lighting product and developing low cost methods to improve the accuracy of these methods. The outcome of this analysis will be an improved test method for estimating the daily operating time for a solar charged off-grid lighting product.

2 BACKGROUND

When we examine the enormous social, political, and environmental challenges faced by society, it is difficult to ignore the fact that over 25 percent of the human population still lives in poverty (World Bank, 2010). This section of the population struggles every day for basic needs like energy required for cooking and lighting. According to the International Energy Agency (IEA), almost 1.3 billion people on the planet have no access to the electric grid and 2.7 billion people live without access to clean cooking facilities (IEA, 2010). Access to affordable and clean energy services and poverty are inextricably interlinked. Therefore, energy access is an important part of addressing issues of equality, development and the environment.

For people that are not connected to the electric grid, the main source of lighting are flame-based lighting devices such as kerosene lamps, oil lamps and candles. These are fossil fuel based technologies and are a cause of many health related issues due to indoor air pollution (IAP). More than one million people a year die from chronic obstructive respiratory disease that develops due to exposure to such indoor air pollution (World Health Organization, 2011). Lighting is a significant source of IAP within households in developing countries (Apple, et al., 2010).

In addition to the health hazards, many of the traditional devices for lighting have poor lighting quality. For example, a traditional candle – that is a light source for millions of low-income rural households – provides an illumination of only one lux at a distance of one meter from the source (Mills, 2005). [1] As a result, the households and businesses that use fuel based lighting devices on a daily basis are negatively affected by the low quality of the lighting services they purchase.

Consumers of flame based lighting account for about 17% of global lighting energy costs but they receive only 0.1% of the resulting lighting energy services in lumen hours (Mills, 2005). Worldwide fuel based lighting costs rural poor around 38 billion dollars each year (Mills and Jacobson, 2007). It is ironic that the poorest section of the human population pays the most for their lighting services.

2.1 Off-grid Lighting

The IEA estimates that with without dedicated additional policies, by 2030 the number of people without access to the electric grid will drop but only from 1.3 to 1.2 billion (IEA, 2010). In the near future this leaves over a billion people in the need for clean and affordable lighting technologies. Adequate light has been socially related to literacy, income generating activities and improved security (Mills, 2005). Hence one way to improve the standard of living of low-income rural populations that have no grid access is to provide clean and affordable alternatives to traditional lighting technologies.

Off-grid lighting technologies like light emitting diodes (LED) and compact fluorescent lights (CFL) have emerged as a bridge between the traditional flame

[1] Illumination is defined as the amount of light incident on a surface measured in lumens per square meter. The unit of illumination is lux. Luminous flux is the total amount of light a lighting device produces in all directions. The unit of luminous flux is lumens.

based lighting and access to the electric grid. LED light sources have become increasingly popular in developing countries due to their low cost, robustness and low energy consumption. They are compact and can be more affordable than CFL based lighting technologies.

Currently, there are numerous commercially available LED and CFL based products with different charging and storage technologies. These products are commonly used for ambient lighting, as flashlights, and also for task lighting in both commercial and domestic applications (Figure 1). A large fraction of these small portable products use solar modules to charge a small battery that runs the lighting product. Furthermore, many of these products have been designed to incorporate grid charging as an additional feature in the product. Thus these products can be charged from a central charging station or independently within the household. The development and commercialization of these products has increased the access of affordable and clean lighting technologies to low income households.

Figure 1: Examples of off-grid lighting technologies that are used for different applications. (Reference: Alstone et al., 2011)

The market for off-grid solar power in developing countries has experienced sustained growth over the past 30 years (Mints, 2009). However, in the last decade tremendous growth in the grid-tied PV market has radically altered the PV market. The overall share of off-grid PV products has declined tremendously from over 90% in 1980 to less than 5% in 2009 (Mints, 2009). With the current boom in the grid-connected sector, the off-grid lighting market has not received much media coverage. However, due to socioeconomic reasons there is a tremendous demand in developing nations for clean and affordable lighting options. In Sub Saharan Africa alone there are nearly 560 million people living off-grid. This provides a huge challenge and a great opportunity for the off-grid lighting market (Lighting Africa, 2010).

2.2 Quality Assurance

As the focus of governments and international development agencies has shifted to off-grid lighting technologies, there has been growing concern over the quality of the low cost lighting devices in the market. One of the caveats to the growth in the off-grid lighting market is the prevalence of low cost but poor quality lighting devices that could result in “market spoiling,” where initial users of these products that come across poor quality lighting products become disillusioned by their performance and do not enter the off-grid lighting market again (Mills and Jacobson, 2007). Regulatory control over the quality of the products entering the market would help reduce this problem.

Over the last few years there has been considerable effort to develop standards and performance metrics to evaluate the quality of off-grid lighting products in the market. Institutes like the Schatz Energy Research Center (SERC), National Lighting Test Center (NLTC), Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE), International Electrotechnical Commission (IEC) and others have been working on developing test methods for the measurement and verification of various aspects of off-grid lighting products. The main sources of funding for these projects have been the U.S. Department of Energy, *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ), World Bank and the International Finance Corporation (IFC). (Lighting Africa, 2012)

Lighting Africa is a program that is working towards improving the market for off-grid lighting products in sub Saharan Africa. Lighting Africa is a joint IFC and World Bank program that is working towards mobilizing the private sector in order to help build a sustainable and healthy off-grid lighting market. The ultimate goal is to create a market for affordable and good quality off-grid lighting products for low-income consumers. Currently the Lighting Africa program has its operations in Kenya, Ghana, Tanzania, Ethiopia, Senegal and Mali. Along with a host of other services, the Lighting Africa program provides testing and technical advisory services to help manufacturers and designers overcome common difficulties faced in designing a product. One aspect of the Lighting Africa program is the development of a quality assurance framework for off-grid lighting products. A combined effort from a number of international organizations has led to the development of the Lighting Africa Quality Test Method (LAQTM). The LAQTM is a detailed set of test methods used to verify the performance and quality of various aspects of an off-grid lighting product. (Lighting Africa, 2012)

2.3 Objective

This study was conducted at SERC with the involvement of the Lighting Africa quality assurance team and SERC employees. The objective of this study fits into the larger goal of the Lighting Africa framework that includes the development of standard test procedures for off-grid lighting products.

This document will present the methods and analysis for estimating the daily operating time for solar charged off-grid lighting products. Daily operating time is one of the performance metrics in the LAQTM. This is an important parameter since it gives an indication of how a product may perform on a daily basis in the field.

Daily operating time or solar runtime (SRT) is the number of hours the lighting product will operate after the product has been charged during the day given a particular amount of incoming solar energy. Due to time and resource constraints, it is not always possible to cycle a product through its full charge discharge cycle in a laboratory to find the SRT of a lighting product.

The Fraunhofer ISE developed a solar runtime model to estimate this parameter in a short span of time and with no additional testing requirements. The Fraunhofer ISE model has been incorporated in the LAQTM. This study seeks to verify the Fraunhofer ISE method for estimation of solar runtime of a lighting product by cycling a number of products through a daily solar charge and lamp discharge cycle.

The Fraunhofer ISE method uses empirically derived efficiency measures for components within the lighting product (PV module, battery, and electronics) to predict the SRT. Since different products perform differently, these empirical efficiency measures have an inherent deviations from measured value associated with them and hence the model has shown some inaccuracies in estimating the solar runtime of lighting products. This analysis builds on the Fraunhofer ISE model with a goal of achieving a more accurate method for estimating SRT with minimum additional testing requirements.

This study also includes methods to determine the solar runtime of lighting products that include accessory charging features. A large number of solar off-grid lighting products provide accessory charging features (e.g. mobile phone charging). Currently, no test standard is available to determine the solar runtime of a lighting product that provides such features.

The outcome of this analysis provides an improved test method for the estimation of SRT of an off-grid lighting product. In addition, the SRT test method and Fraunhofer ISE calculation model are amended to incorporate the possibility of accessory charging features in a lighting product.

3 TESTING OVERVIEW

There are a number of international test methods applicable to the off-grid lighting market. The two test methods relevant to this study are the Global Approval Program for Photovoltaics (PVGAP) recommended specification for solar lights and the Lighting Africa Quality Test Method (PVRS – 11A, LAQTM version – 2.01). The PVRS – 11A test method is suitable for portable solar lanterns used in indoor lighting applications. The description of a solar lantern in the document is loosely stated as "lighting system consisting of a lamp (mainly CFL), a lead-acid or nickel-metal hydride (NiMH) battery and electronics, all placed in a suitable housing made of durable material such as metal or plastic and an integrated or separate PV module." (PVRS – 11A) In contrast the LAQTM is a test method for evaluating the performance of off-grid lighting systems, lamps (mainly LED), batteries, charge controllers, and PV modules. Relevant details of these test methods will be discussed in this section.

3.1 LAQTM Test Method

The Lighting Africa Quality Assurance Program is designed to evaluate the quality and performance of off-grid lighting products and to communicate information about product quality to buyers and other stakeholders. It includes a complete set of test procedures for the testing of various aspects of an off-grid lighting product. The LAQTM is a detailed set of test methods used to verify the performance and quality of off-grid lighting products.

The main aspects of a lighting product that are tested in the LAQTM are lighting service, usability, and durability of the product (Figure 2). Each of these aspects is associated with a minimum standard and/or recommended performance target. The standards and targets set thresholds for quality and performance for off-grid lighting products. Products that meet the standards and targets are eligible for business services through the Lighting Africa program.[2]

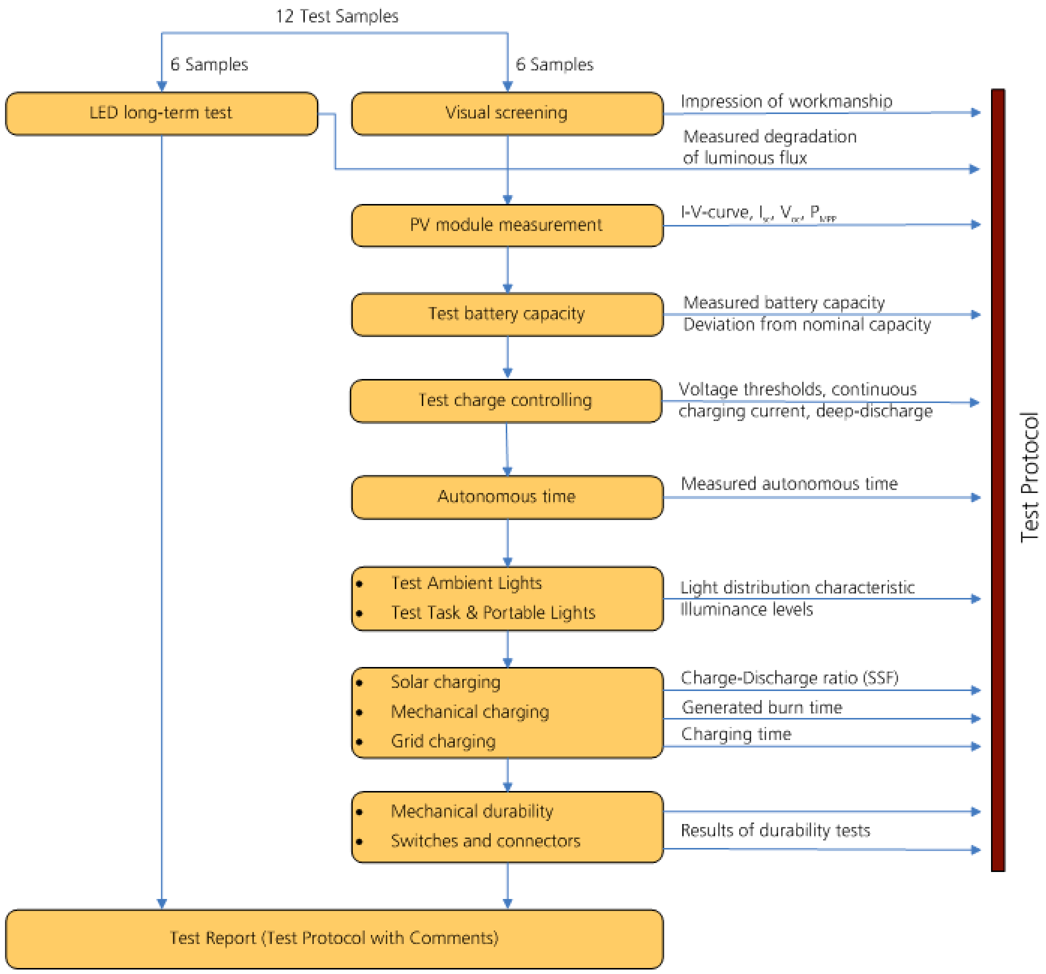

Figure 2: Overview of test procedures and measurement for LAQTM (Reference: LAQTM version – 2.01)

[2] For more information on minimum standards and performance targets visit http://www.lightingafrica.org/product-quality-assurance-/product-testing-and-performance-verification.html

One of the key aspects tested in the LAQTM is the energy system performance of an off-grid lighting product. The components of the energy system (e.g., the battery, PV module and electronics) are tested individually and as a system. These tests are especially important to the SRT measurement as they act as inputs to the performance model. The test methods and associated LA recommended performance targets for the energy system components are discussed below.

3.1.1 Component level tests

These tests evaluate each component of the energy system of the lighting product individually. The LAQTM component level tests are described below.

3.1.1.1 Lighting Product Battery.

The battery is tested separate from the lighting product for its capacity in ampere-hours (Ah). The test involves cycling the battery through a number of charge and discharge tests using a battery analyzer. Different battery types have different test procedures under the LAQTM. For example, a nickel metal hydride battery undergoes a conditioning process of three cycles of charge and discharge before the battery capacity test. This cycling is not included in the test for sealed lead acid batteries. The battery capacity is determined by measuring the ampere-hours delivered by the battery after receiving a full charge. The measured capacity is compared to the rated capacity to determine if the battery is damaged or if the rating is correct.

3.1.1.2 Lighting Product PV module.

The PV module is tested for its rated power and to determine the characteristic current-voltage (I-V) curve. Besides the maximum rated operating power point of the PV module, the curve determines the open circuit voltage and short circuit current for the module. This information is used to determine if the PV module is damaged or if the rating is correct. The general range of PV modules tested for off-grid lighting products is from 0.3 W to 10 W. The test is conducted using an I-V curve analyzer that records the module current and voltage over the full range of loads.[3]

3.1.1.3 Lighting Product charge controller.

The lighting product is examined to determine if it has deep discharge or over voltage protection built into the charge controller. This is important for safety (e.g., especially in the case of a Li-ion battery) of the lighting product and to increase the life of the battery (LAQTM version – 2.01). The lamp of the lighting product discharges the battery and the voltage is monitored to ensure that the product has low voltage protection. In order to maintain a minimum recommended voltage, the charge controller must have a built-in low voltage disconnect (LVD) circuit. Similarly when a maximum allowable voltage is reached for a particular battery, an over voltage protection (OVP) device must prevent the battery from receiving any additional charge. There are specific recommendations for the OVP and LVD for different battery chemistries.[4] This test does not have any recommended targets associated with

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[3] The test data is corrected for standard test conditions i.e. 1000 w/m^2 and panel temperature 25 degrees Celsius

[4] LVD thresholds of 1.87 V±0.05V/cell for Lead-acid batteries, 3.00 V±0.05V/cell for

it. However, manufacturers are strongly urged to incorporate the OVP and LVD in their product design.

3.1.2 System Level Tests

These tests include a combination of two or more components of the energy system of the lighting product. The LAQTM system level tests are described in this subsection.

3.1.2.1 Autonomous Runtime (ART) test

The autonomous runtime of the product is defined as the number of hours the lighting product will run on a fully charged battery until it reaches seventy percent of the initial light output.[5] The ART is a key metric for assessing the lighting product performance. The test combines the battery capacity and the energy required to run the light and informs the user about product usability. The test involves running the light with a fully charged battery and measuring the variation in the luminous flux of the lighting product. The time that it takes the flux value to reach 70 percent of its initial value is reported as the ART of the lighting product (Figure 3).

Li-ion batteries, and 2.00 V±0.05V/cell for LiFePO4 batteries are recommended. Similarly OVP cut-off levels of 2.42 V±0.05V/cell for lead-acid batteries, 4.10 V±0.05V/cell for Li-ion batteries, 3.60V±0.05V/cell for LiFePO4 batteries are recommended. (LAQTM Test Procedure Version-2.01)

[5] The Autonomous Runtime test is also refered to the “Full battery runtime test” in the LAQTM version – 2.01 document.

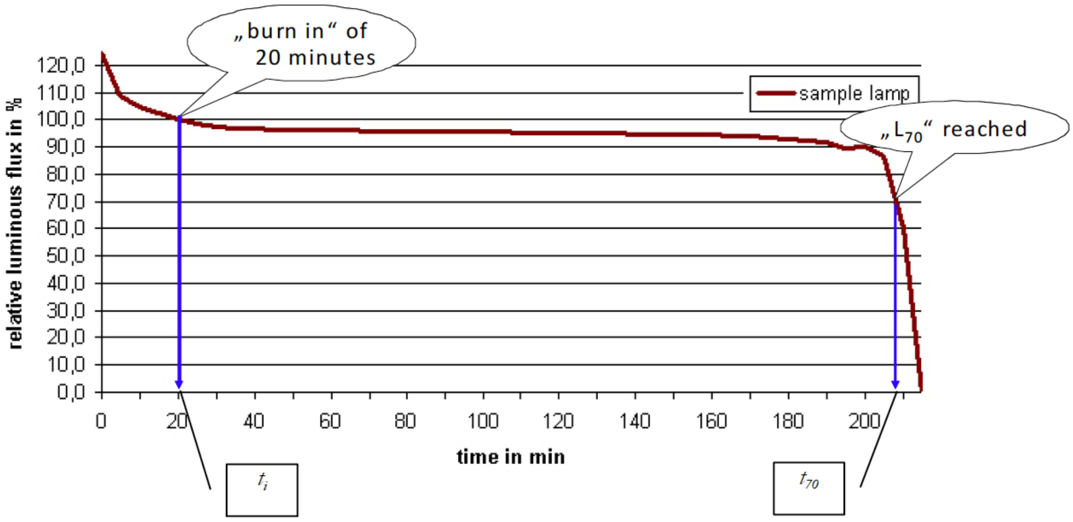

Figure 3: Figure showing how the autonomous runtime is calculated. L_{70} is 70 percent of the luminous flux value after 20 minutes of starting the lamp. t_{70} is the time it takes for the lamp to reach the L_{70} value, which is the autonomous runtime for the lighting product (Reference: LAQTM version – 2.01).

3.1.2.2 Solar Runtime Calculation.

The daily solar runtime is estimated using a model for predicting the daily runtime of a solar off-grid lighting product given a certain number of sun hours in the day.[6] It is an important parameter in the performance evaluation since it informs the consumer about the usability of a lighting product by combining the performance and capacity of different components within the device. The efficiency of various components (PV module, battery and electronics) in the lighting product determines what fraction of the incident energy is stored and used to run the light source. The solar runtime estimation model combines these efficiencies, the battery capacity, and the PV module rating to estimate the hours of operation of a lighting product in the night.

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[6] Sun Hour is defined as the amount of solar radiation incident on the surface of the earth and is measured in kWh/m^2-day.

3.2 Current SRT Test Methods

The solar runtime calculation is the object of analysis in this study. It is not always possible to determine the SRT by cycling a product through its full charge discharge cycle in a laboratory due to time and resource constraints. The Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) and the Global Approval Program for Photovoltaics (PV GAP) have developed test methods which include solar runtime models to estimate this parameter in a short span of time and with minimum additional testing requirements. The Fraunhofer ISE model was developed as an alternative low cost method to the PV GAP method (since it takes lesser time in terms of testing and equipment/personnel time). This study attempts to verify the Fraunhofer ISE method for estimation of solar runtime of a lighting product by cycling the product through its daily solar charge and lamp discharge cycles. The PV GAP method is also studied for comparison with the Fraunhofer ISE model.

3.2.1 Abbreviated PV GAP Test Method

PV GAP is a not for profit organization that works in the field of solar photovoltaic technology. The organization works with a number of government and private stakeholders around the world to improve quality and increase access of PV technology (PV GAP, 2012). One of the key roles the organization plays is to develop and promote the use of internationally accepted quality standards for PV technology. Abbreviated PV GAP Recommended Specification (PVRS 11A, solar lights, 2012) is a performance test method for portable solar lanterns that use CFL.

Portable solar lanterns are described as devices that contain a light source, battery and drive electronics in an enclosed casing along with a PV module for charging. The lighting product is tested as a system and also by component for performance and durability. Performance testing of the lighting product includes using a programmable power supply to charge the lighting product battery. The power supply is intended to simulate solar charging of the device. This is achieved through current controlled charge - also called daily irradiance profiles - and lamp discharge of the lighting product battery for a specified number of hours for ten days (Figure 4). The programmable power supply simulates a solar charge for a resource of 1, 5 and 6 kWh/m^2-day. This test gives a number of performance factors for the lighting product along with SRT at different irradiation profiles.

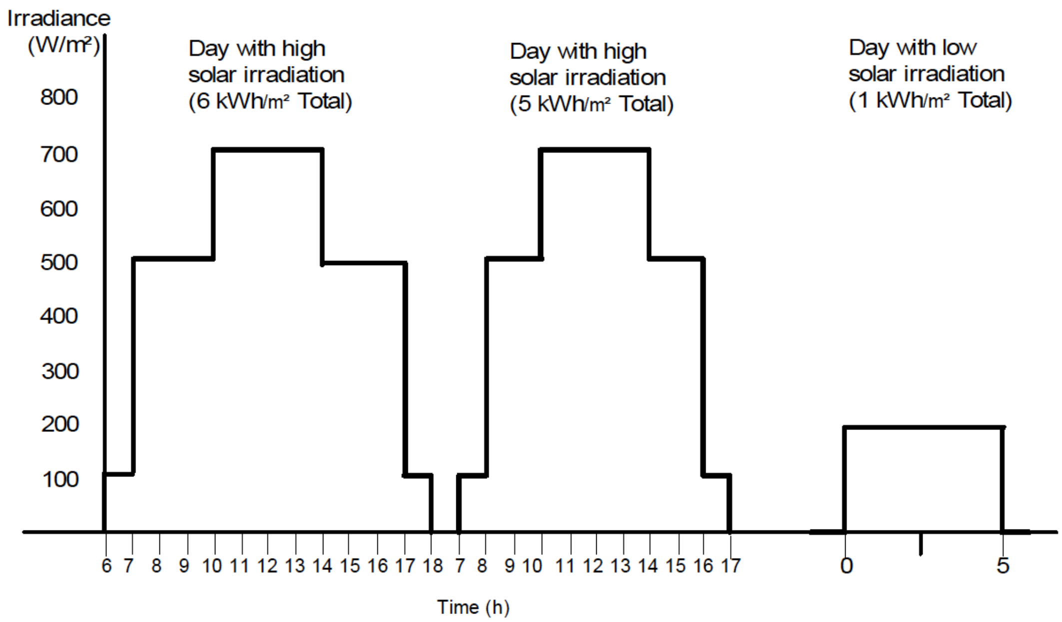


Figure 4: Abbreviated PV GAP daily irradiance profiles for the performance testing of portable solar lanterns (Reference: Abbreviated PV GAP PVRS 11A)

The PV GAP method requires a total of ten days of charge cycles for each of the samples of the lighting products tested. In this study, a shortened version of the PV GAP method is used, which uses the irradiance profile of 5 kWh/m^2-day for one day to predict the SRT of the lighting product. The lighting product is discharged after it is charged with a rate consistent with 5 kWh/m^2-day and the time of discharge gives the estimate of SRT. The shortened version of the PV GAP procedure is used in this study since it takes less personnel/equipment time to run than the full PV GAP test. The 5 kWh/m^2-day portion of the PV GAP method is used because this is a standard interval for reporting SRT for lighting products. Hereafter, the shortened version of the PV GAP method will be referenced as the “abbreviated PV GAP method”.

3.2.2 Fraunhofer ISE Model

Fraunhofer ISE is a solar energy research institute based in Germany. The institute works on research and application based projects in the field of solar energy. Fraunhofer ISE is a partner in the Lighting Africa program that was contracted to test and develop standard test methods for off-grid lighting products for the African market. The Stand Alone LED Lighting Systems Quality Screening document - Test procedure – Version 2.01, 2010 - describes methods to test various aspects of off-grid lighting products. The three main aspects of a lighting product tested are: lighting service, durability and usability. Lighting service tests measure the quality of light that the product gives, for example light distribution and luminous flux measurements. The durability tests on the lighting product measure the robustness of the product and possible impacts during daily use. Finally, the lighting product is tested for features like the charging behavior that measure aspects like the amount charge/discharge time for a product with PV, grid or mechanical charging.

Fraunhofer ISE developed a low cost method for evaluating the PV charge behavior of a lighting product. A solar lighting product must have its PV module, battery and lamp sized appropriately to give the best results as a system. To understand this interaction the solar runtime (SRT) and simplified solar fraction (SSF) of a lighting product are estimated. The simplified solar fraction is simply the ratio of the daily charge to the daily discharge of a product (in amp-hours) as a percentage.

$$\mathrm{SSF} = \frac{\text{Daily Charge (Ah)}}{\text{Daily Discharge (Ah)}} \times 100 \qquad \text{Equation 1}$$

Where:

Daily Charge is the amount of charge received from the solar panel into the battery in ampere-hours

Daily Discharge is the amount of discharge from the battery to the lamp in ampere-hours

A SSF value close to one hundred percent indicates that the PV module is sufficiently sized to charge the battery of the lighting product in one solar day. However, a SSF value that is much lower or higher than hundred percent can provide information about a mismatch between the solar panel and the battery chosen for the lighting product. Fraunhofer ISE has developed an excel tool to estimate the daily charge and discharge for a lighting product. The inputs to the tool include average daily solar resource, PV module dimension, PV module rated power, autonomous runtime, required runtime and measured battery capacity of the lighting product.

Another way of looking at the PV charging performance of the lighting product is by estimating the SRT. Similar to SSF, Fraunhofer ISE has developed an excel tool for estimating the SRT for a lighting product (Figure 5). The inputs to the tool include average daily solar resource, PV module rated power, autonomous runtime, and battery type/measured battery capacity of the lighting product. The SRT model assumes empirically determined performance factors for the conversion efficiencies within the product. These conversion factors take into account the PV module, battery and electronics performance of the lighting product (Figure 6).

Solar Run Time Calculation		
Method	LAQT 2.0 *based on model by FISE*	***Notes***
Test Conducted by		**Fill out Green boxes for Input**
Date		**Read output from yellow boxes**
Location		
Sample ID Code:		
CALCULATION INPUTS		
Battery Type	Lead-Acid	<- Choose type from pull-down
Battery Voltage [V]	4	
Battery Capacity [mAh]	1200	
Autonomous Time [h]	10.0	
PV Power [W]	1	
CALCULATION RESULTS		
Daily Solar Run Time [h]	6.5	
Percent of a full battery charge received from solar day	65%	
CALCULATION ASSUMPTIONS AND CORRECTION FACTORS		
Solar Day Energy (number of full sun-hours) [kWh/m2-day]	5	<- 5 kWh/m2 is the standard day
Charging Performance [%]	0.9	
Discharging Performance [%]	0.86	
PV MPP Losses [%]	0.8	
Correction Factor [%]	0.6192	
PV Energy [Wh]	3.096	
Battery Energy [Wh]	4.8	
Battery Type	Charging performance coefficient	
Lead-Acid	0.9	
Li-Ion	0.9	
NiMH	0.75	
NiCd	0.75	

Figure 5: Screenshot of the Fraunhofer ISE Excel Tool for calculating the daily solar run time with example inputs (Reference: LAQTM Test Procedure – Version 2.01, February 2011)

The following steps are described in the LAQTM procedure (LAQTM Test Procedure – Version 2.01, pg. 43) to use the tool:

- Enter test –related information in the first set of green boxes (Figure 5).
- Enter characteristics of the battery, PV module, and autonomous run time in the green boxes in the “Calculation Inputs” section. Note that there is a drop-down selection box for battery type (chemistry).
- Read the results from the “Calculation Results” section.

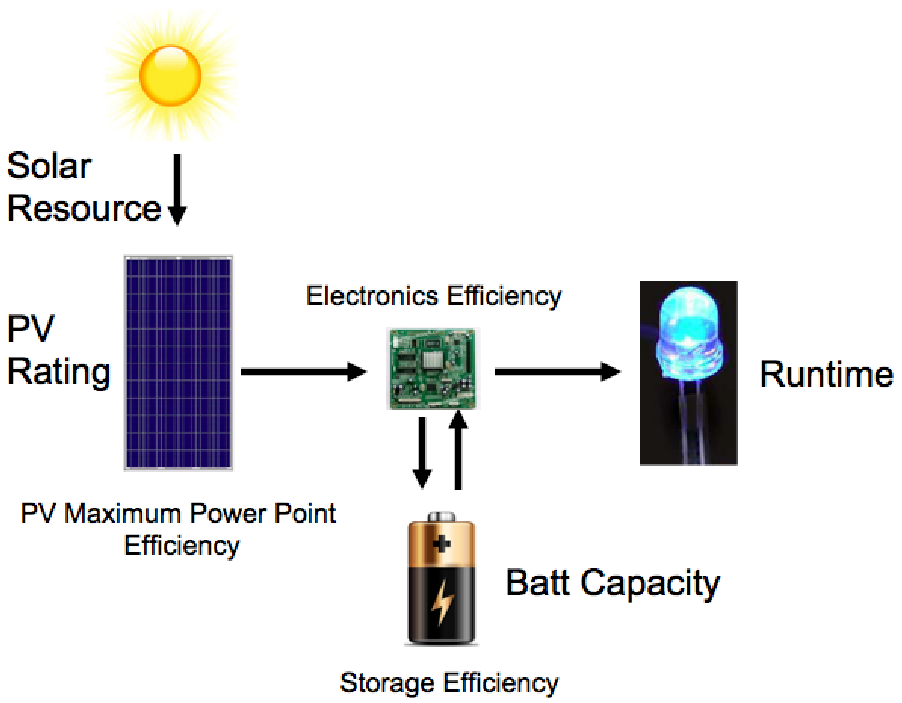


Figure 6: Fraunhofer ISE model energy flow with the inputs and built-in correction factors for the component efficiencies of the lighting product.

For converting the solar resource to actual energy delivered from the PV module, a correction factor of 80% is assumed for all products.[7] Another factor taken into account in the calculation is the storage efficiency of the lighting product battery. The Fraunhofer ISE model uses battery performance factors based on the battery chemistry of a lighting product. Model estimates for sealed lead acid (SLA) and Lithium ion (Li-ion) battery charge-discharge efficiency are 90% and estimates for nickel metal hydride (NiMH) and nickel cadmium (NiCad) batteries are 75%. Finally, the electronics charging performance of 86% is assumed for all off-grid lighting products.

$$\mathrm{SRT} = \mathrm{CF} \times \frac{\mathrm{EPV}}{\mathrm{EBatt}} \times \mathrm{ART} \qquad \text{Equation 2}$$

where,

SRT is the solar runtime for the lighting product in hours

CF is the combined correction factor (PV_{mpp}, electronics and battery efficiency) for the lighting product

E_{PV} is the energy delivered to the battery from the PV module of the lighting product in watts

E_{Batt} is the total amount of energy that can be stored in the battery of the lighting product in watts

ART is the autonomous runtime of the lighting product in hours

The Fraunhofer ISE model for estimating SRT draws from the results of other tests and does not require any additional information for the calculation. Hence it is a

[7] The maximum power point of a PV module is determined from its IV curve. It is the point on the IV curve where the PV module delivers the maximum power to the load.

very low cost option for estimating SRT. Abbreviated PV GAP test method on the other hand requires at least ten charge/discharge cycles (each charge cycle can last for 12 hours). Depending on the lighting product these tests can last for multiple days. To test more than one product at a time, this test will require multiple power supplies (charge cycle) and dark boxes (discharge cycle). In addition, the data generated would need a considerable amount of labor to analyze. One option is to run the Abbreviated PV GAP method only for one cycle of charge (5 kWh/m^2-day) and use the STR estimates from this cycle. This study attempts to verify and build on these methods for accurate estimation of SRT of a lighting product at a low cost.

A number of lighting products have mobile phone charging features included in their design. This feature changes how the product operates since part of the PV energy may be used to charge the accessory device. An effort has been made in this study to modify the SRT model so as to be able to capture the effect of mobile phone charging. The research methods used in this study will be discussed in the following section.

4 METHODS AND MATERIALS

In order to verify the accuracy of the Fraunhofer ISE model, a number of off-grid lighting products were tested at SERC. The first phase of testing included running a product through its solar charge cycle during the day and lamp discharge cycle in the night. The products selected represented a wide variety of solar panels, battery chemistries and charging electronics. Seven products were cycled through solar charge and lamp discharge during the testing phase. The SRT values measured during this outdoor testing were compared to the Fraunhofer ISE model estimate. The results showed that the model estimates for prediction of SRT are inaccurate. This prompted a second phase of testing to improve SRT estimates from the model.

The subsequent phase of testing included developing methods to improve the model estimate with minimal increase in the testing requirement. This phase also includes comparison of the Fraunhofer ISE and the abbreviated PV GAP method for estimating SRT. Based on the results of this phase of testing, recommendations have been made to amend the current Fraunhofer ISE model for SRT estimates of solar lighting products. The new method will include additional tests to estimate the component efficiencies within the lighting product.

This study takes a step further in the SRT analysis of lighting products by attempting to model the effects of mobile phone charging on the runtime. An increasing number of off-grid products introduced into the market have incorporated mobile phone charging features. The introduction of this feature changes how off-grid lighting products perform since the energy produced by the PV module is now divided between charging the lighting product battery and the mobile phone. Specifically, the SRT of lighting products will be affected with this new feature. Hence it is important to capture the effect of mobile phone charging on the performance of the lighting product. Currently there is no testing method that details how to capture the effect of mobile phone charging on the performance of an off-grid lighting product. The proposed change is to modify the SRT calculation model so as to capture the effect of mobile phone charging.

This section describes the methods and materials used in the different phases of testing during the course of the study. See Appendix A

Table A5 for details about the instrumentation used in this study.

4.1 Phase One: Verification of Fraunhofer ISE model for SRT

The first phase of testing involved outdoor testing of solar charged off-grid lighting products in order to verify the Fraunhofer ISE model for SRT estimation. The verification method included charging the lighting product with the PV module during the day and then discharging the lighting product battery with the lamp. The charge cycle constituted charging the product for seven hours during the day (from 9:30am to 4:30pm), and the discharge cycle constituted running the lamp until a minimum allowable low battery voltage was reached. For products that did not have a low-voltage disconnect, a variable low voltage disconnect device was incorporated in the circuit. This enabled uniform charge/discharge cycles throughout the testing phase. The time that it took for the battery to reach its minimum allowable voltage or for the lamp to reach 70 percent of its initial illumination – the lesser of the two – was reported as the SRT of the lighting product (Figure 7).

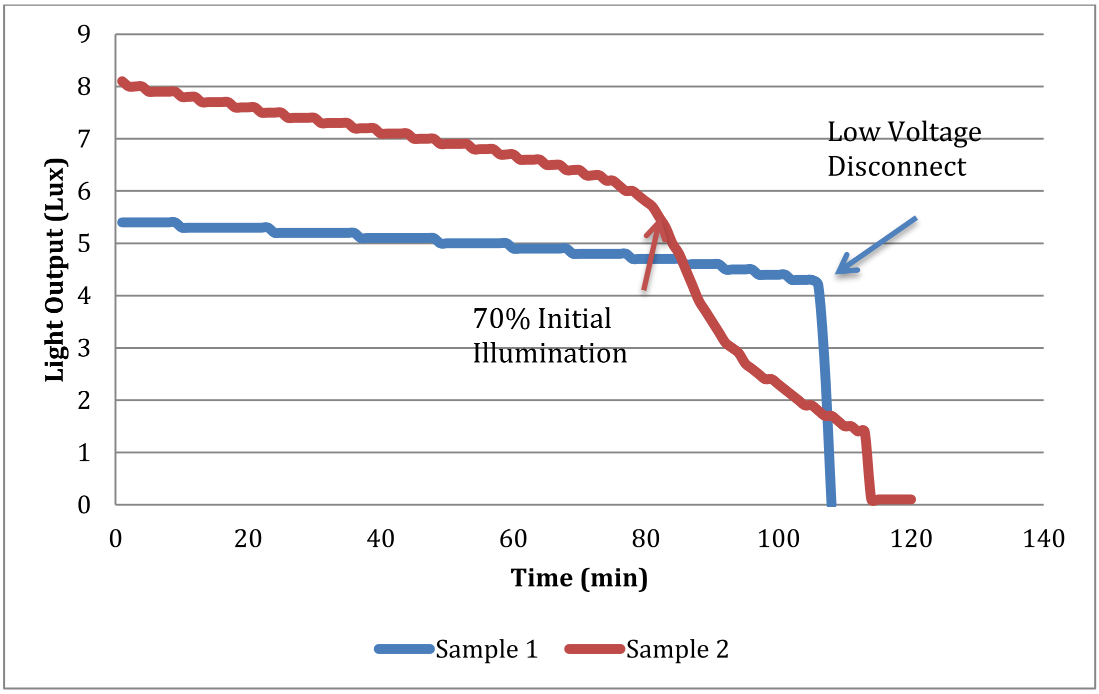


Figure 7: Figure shows discharge curves of two products where sample 1 has a built in low voltage disconnect device and sample 2 does not have a low voltage disconnect device.

The charge discharge cycles were divided into two batches. When one batch was solar charged outdoors during the day the other was discharged indoors in the laboratory. All the products completed their charge discharge cycle in two days. Special care was taken to clean the PV modules and the pyranometer every morning to ensure no water or dust affected the readings. The outdoor testing phase was conducted over a month, with each product tested over seven or eight charge-discharge cycles.

The products chosen for the verification of SRT model were those that had undergone the battery capacity, IV curve and autonomous runtime test. These parameters serve as inputs to the solar runtime calculation model. Energy flows during the charge and discharge cycles at various points in the lighting product were monitored to enable an energy analysis of the cycles. The solar resource and the current and voltage measurements into and from the product battery during the charge-discharge cycles were used in the energy analysis. The results of the runtime measured during the discharge were then compared to the estimate from the Fraunhofer ISE model for SRT of the lighting product.

4.1.1 Tested Products

Seven products were cycled through solar charge and lamp discharge during the first phase of testing. The products selected were taken so as to represent a wide variety of solar panels, battery chemistries and charging electronics. Among the seven products tested, six are LED-based lighting products and one is a CFL based product. The battery chemistries tested included SLA, NiMH, NiCad and Li-ion (Table 1). The PV module types tested included mono-silicon, poly-silicon and amorphous silicon modules, with a power rating that ranged from 0.3W to 6.0W. Each of the products is referred by a code name in the remainder of this study.

Table 1: Details of lighting products tested in the first phase

Product Picture	Product Name/Model Number	Battery Type/Capacity	PV Module Type/Capacity	Lamp Type
	Solar Flashlight HSI 106	NiMH (310 mAh)	Mono-silicon (0.34W)	LED
	Tough Stuff Room Lamp Kit	NiMH (1500 mAh)	Amorphous-silicon (1.2W)	LED
	Udaymini CZS 102	SLA (4500 mAh)	Poly-silicon (6.0W)	CFL
	K-light	NiMH (1600 mAh)	Poly-silicon (1.8W)	LED
	Solata Solar LED Lantern	NiCad (400 mAh)	Poly-silicon (0.6W)	LED
	Sunlite Solar Light	LiIon (3000 mAh)	Mono-silicon (2.9W)	LED
	Solar Lamp and mobile phone charger ST1	SLA (2800 mAh)	Mono-silicon (1.5W)	LED

4.1.2 Experimental Setup

A special test rack was built for PV charging of the lighting products (Figure 8). The rack was built such that it housed the PV modules of the seven products and a pyranometer – for solar resource measurement – in the same plane. The test rack was fixed with the PV modules facing due south and tilted at an angle approximately equal to the latitude of the region (Arcata Latitude = 40.87°N).

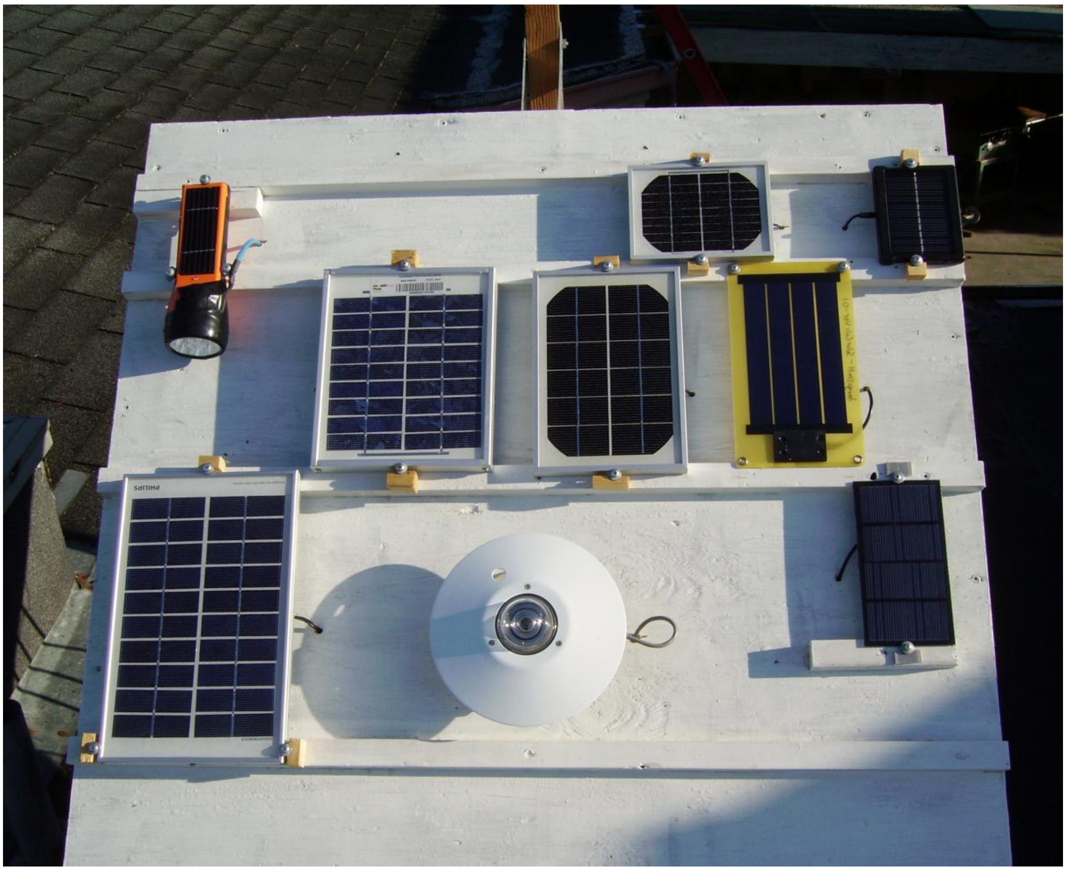


Figure 8: Picture of the test rack used in first phase of testing for PV charging of the lighting products

During the charge cycle, current to the product’s battery from the PV module was measured using a transducer and the voltage was measured across a voltage divider. An Onset HOBO® data-logger recorded the real-time values of the current and voltage at one-minute intervals (Figure 9). The voltage from the pyranometer was recorded using a Fluke-87 multi-meter and converted into solar resource using the pyranometer calibration coefficient.

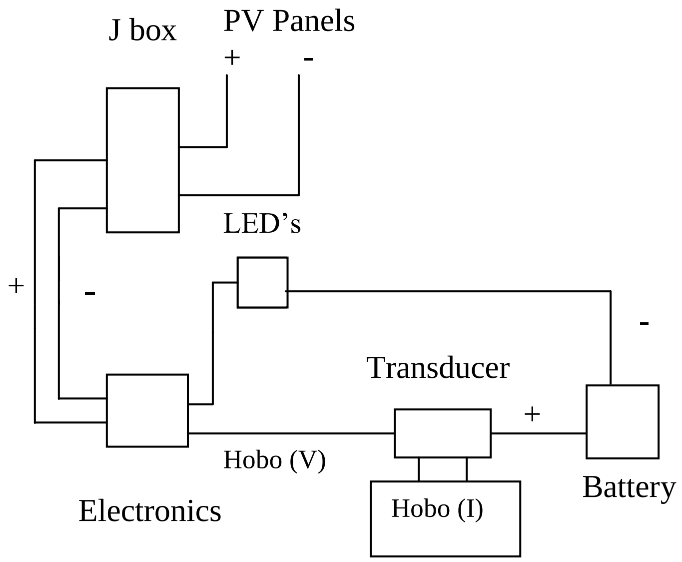


Figure 9: Block diagram of the experimental setup for solar charge cycle

Each of the products was discharged in a dark box setup in the laboratory (Figure A20). The dark box setup is used for the ART measurements in the SERC laboratory. The setup enables relative illuminance measurements of a lighting product at a distance of one meter from the light source. Incorporated within the dark box setup is a transducer and voltage divider to enable monitoring of the current and voltage from the lighting product battery (Figure 10). An Onset HOBO® data-logger recorded the real-time values of the current and voltage at one-minute intervals. A low-voltage disconnect device was added to this setup in case any of the lighting products did not have this feature.

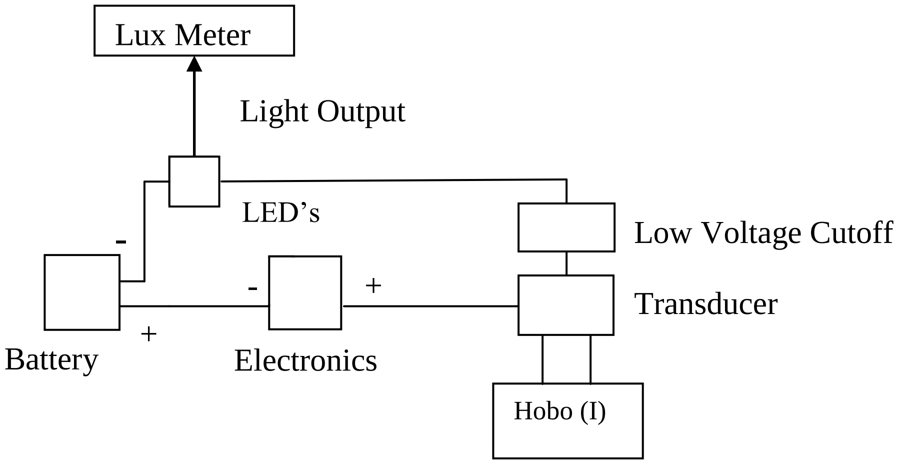


Figure 10: Block Diagram of the experimental setup for product discharge cycle

4.1.3 Measured Parameters

During the charge cycle a Fluke-87 high precision multimeter was used to measure the voltage from the pyranometer. Energy from the PV module was determined by using the measured solar resource and maximum power point of the module. The transducer and voltage divider setup explained above were used to measure the current and voltage into the lighting product battery. Thus the energy input into the battery from the PV module was calculated. The two measurements gave information of the component level flow within the lighting product during the charge cycle.

During discharge the current and voltage from the lighting product battery to the lamp was data logged with a similar transducer and voltage divider setup used in the charge cycle. Illuminance measurements from the lighting product lamp were made using an Extech light sensor in the dark box setup.

Measurements at the different points within the lighting product enabled a study of the energy flow within the device during the charge and discharge cycles. The results showed that the Fraunhofer ISE estimates of SRT for the products tested were not consistent with the experimental values (Section 5.1). The analysis of the energy flow data also indicated that the main cause of the deviations from measured value in the Fraunhofer ISE model was the inaccurate estimates of the lighting product performance factors (i.e. PV maximum power point efficiency, electronics efficiency, and battery efficiency). The next phase of testing was aimed at accurate estimation of the performance factors for the lighting product with minimal additional testing overhead.

4.2 Phase Two: Revision of Fraunhofer ISE model for estimation of SRT

From the outdoor testing of the seven products it became clear that the main deviations from measured values in the Fraunhofer ISE model for determining SRT is the assumptions of the PV_{mpp} factor, and electronics and battery efficiencies of a lighting product. To improve the accuracy of the Fraunhofer ISE model for SRT, better estimates for the performance coefficients in a solar lighting product are required. This section details revision made to the Fraunhofer ISE model to improve the accuracy of the solar runtime estimate.

4.2.1 Average Cycle efficiency

In the first revision, average values of the battery efficiency, PV_{mpp} efficiency and electronics efficiency for the outdoor charge-discharge cycles tested are used in calculating the overall performance factor of the product. Since the average values of actual solar charge and lamp discharge cycles are used, the SRT estimates from this revision will give the most accurate results in a proportional model. However, using this method will require a number of hours for a charge-discharge cycle (e.g. seven hours for charge cycle) along with good solar resource (i.e. relative sunny conditions)) in the test area. Hence, further improvements to the SRT model are aimed at achieving this accuracy with minimum changes to the LAQTM.

4.2.2 Single Point Efficiency

This revision introduces three single point measurements in the test method. The assumption is that these single point efficiencies will provide a more realistic measure of the average component efficiencies for a lighting product than the empirical values used in the Fraunhofer ISE model with minimum additional testing overhead.

The three factors used in this revision to calculate the overall performance factor of the product are PV_{mpp}, electronics, and battery efficiency. As compared to the original Fraunhofer ISE method, the single point tests require 30 minutes of additional personnel time per unit tested. Refer to Appendix B for detailed test methods developed for each measurement.

4.2.2.1 PV_{mpp} Efficiency Test

The PV_{mpp} test was developed to get an estimate of the actual operating power point of a PV module in the charge cycle. The PV module may not operate at its measured maximum power point (MPP) value – estimated in the IV curve test – due to a mismatch between the load and the PV module output and due to the operating temperature of the PV module. The test is designed to get a single operating point of the PV module close to the mid-point of the charge cycle. The assumption is that the efficiency at this point will provide a good estimate of the average PV_{mpp} efficiency observed during the charge cycle.

The method for estimating the PV_{mpp} efficiency is briefly described below.

- Before the test, the battery of the lighting product is brought to a 50 percent state of charge. This can be done using a battery analyzer or simply discharging a fully charged product battery for half the autonomous runtime using the product lamp.

- On a clear day the PV module voltage is measured when connected to the lighting product battery (at 50 percent charge). The panel temperature and solar resource are noted during this measurement.

- The measured voltage is then corrected for standard test conditions.[8]

- The power corresponding to the voltage recorded is found from the IV curve and the ratio of the operating power to the MPP from the IV curve is the PV_{mpp} efficiency for the product.

4.2.2.2 Electronics Efficiency Test

The electronics of a lighting product conditions the current and voltage from the PV module before charging the battery. In this process, there is a loss of energy that needs to be accounted for within the SRT module. The single point efficiency measurement in this test gives an estimate of the average efficiency of the electronics during the charge cycle. The electronics efficiency is the ratio of energy delivered to the battery over the energy supplied by the power source. The test is done when the battery of the lighting product is at 50 percent state of charge.

The method for estimating the electronics is briefly described below.

- The lighting product battery is charged with a programmable power supply. The input voltage and current is from the PV_{mpp} test.

- The current and voltage provided by the power supply and entering into the battery are recorded at regular intervals (four readings over one minute).

[8] Standard Test Conditions is defined as a solar resource of 1000 W/m^2, with a module temperature of 25°C. The correction factor was tailored for each of the different types solar panels tested.

- The ratio of the average power provided to the battery over the average power of the power supply will give the electronics efficiency measurement of the lighting product.

4.2.2.3 Battery Efficiency Calculation

The battery efficiency calculation is made to estimate the losses in the charge and discharge cycle of the lighting product battery. This calculation is made using data collected in the battery capacity test. The battery efficiency is the ratio of the energy given out by the battery over the energy delivered to the battery in one charge-discharge cycle. The battery should be primed and should have undergone at least two complete charge-discharge cycles to get reliable data for the battery efficiency calculation.

4.2.3 Abbreviated PV GAP Method

This revision uses the Simulated Solar Charge experiment, which is derived from the Abbreviated PV GAP test procedure. The method uses a single 12-hour cycle to charge a lighting product using a programmable power supply. The power supply mimics a typical solar charge day by using a step function for the current (Table 2). Each of the seven products used in the Fraunhofer ISE verification experiment were tested using this method. The runtime values achieved during this test are compared to the actual values from the outdoor testing phase. The accuracy of the estimation for SRT of this method is then compared to results from the original and revised Fraunhofer ISE model.

Table 2: Step function used to charge a lighting product in the Simulated Solar Charge Test

Time (hours)	Charge Current (% of i_{mpp})	Irradiation (W/m^2)
1	10%	100
3	50%	500
4	70%	700
3	50%	500
1	10%	100

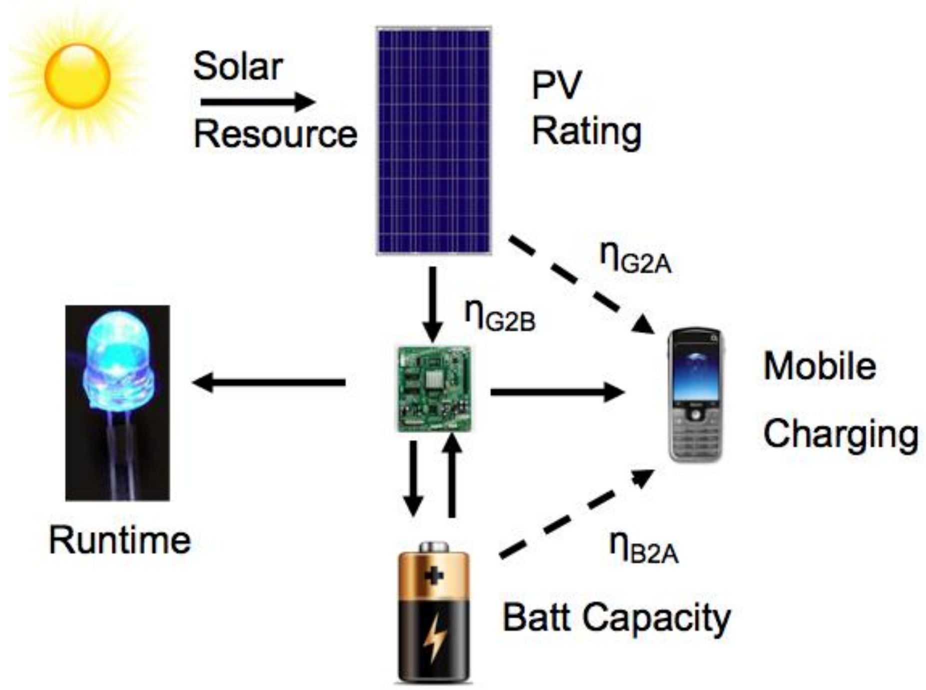
One complete cycle represents one solar day of charging. The charge cycle chosen for this test was for a solar resource of 5 kWh/m^2-day. After each charge cycle, the product is discharged in the dark box. The time required for the product to reach its minimum voltage or for the light source to reach 70 percent initial lighting level – lesser of the two – is recorded as the SRT for the charge cycle. The SRT is then normalized for the solar resource observed during the outdoor charge cycles.[9] Finally the accuracy of the three methods are compared and analyzed.

4.3 Estimation of SRT with Mobile phone Charging

Many off-grid lighting products are designed with the option of powering additional auxiliary uses such as mobile phones, radios, and televisions. The option of charging mobile phones is extremely common, which calls for an assessment of how the product's SRT is affected by utilizing the mobile phone charging feature.

[9] The Abbreviated PV GAP runtime was normalized for outdoor charge cycles that had a solar resource of 4.5 to 5.5 kWh/m^2-day.

The mobile phone can be charged from the lighting product PV module or battery. Depending on the two different pathways for charging the mobile phone, there is an associated efficiency loss between the lighting product and the mobile phone.



Key

η_{G2A} is the mobile charging efficiency from the lighting product PV module
η_{B2A} is the mobile charging efficiency from the lighting product battery
η_{G2B} is the charging efficiency of the lighting product battery from the PV module

Figure 11: Block diagram showing the energy flow of an off-grid solar charged lighting product that includes mobile phone charging as an accessory feature.

In order to determine the SRT of a lighting product, some simplifying assumptions were used to model the charge behaviour of a lighting product that includes mobile phone charging as an additional feature.

- For a full mobile phone charge, use 4.8 watt-hours (Wh) for the energy input into the mobile phone phone and for receiving half a mobile phone charge, use 2.4 Wh. These values are typical for a mobile phone.

- Assume the fraction of the daily energy (Alpha: α) received by the mobile phone directly from the PV module to be 50%[10]. This means that accessory charging is split evenly during night and daytime. If the lighting product does not include accessory charging at night as a feature then assume $\alpha = 1$, and if lighting product has no solar charging option for accessories assume $\alpha = 0$.

The factor Alpha can be determined from the electronics efficiency test. This fraction will give an estimate of how much of the energy that flows to the mobile phone comes from the lighting product PV module as opposed to the battery. Then by applying the charging efficiency to each of these pathways, the model estimates the losses in energy that occur while charging the mobile phone and in effect the amount of energy available to run the lighting product lamp.

The model uses the same three component efficiency factors used in the Fraunhofer ISE model to calculate the overall performance factor of the lighting product. The method for calculating the PV_{mpp}, and battery efficiency are the same as

[10] The value of Alpha (α) is highly uncertain and is related to the number of hours and time of use of the auxiliary device and the auxiliary charging behavior of the consumer.

described in the revised Fraunhofer method. However, the electronics efficiency test is modified in order to determine the electronics efficiency of the energy pathway from the PV module and the battery to the mobile phone. Refer to Appendix B for the detailed test method to estimate the electronics efficiency of a lighting product with mobile phone charging features.

5 RESULTS AND DISCUSSION

In this section, the Fraunhofer ISE model for estimating SRT are compared to experimentally measured values. Possible reasons for the deviations of the Fraunhofer ISE model from the measured value will be discussed and also remedial measures for the same. Finally, a comparison are made between the Fraunhofer ISE model, revised Fraunhofer ISE model, and Abbreviated PV GAP method for estimating SRT for solar charged off-grid lighting products. On the basis of these results, a set of improved test methods for estimating SRT for off-grid lighting products and next steps for the study are proposed.

5.1 Fraunhofer ISE Solar-runtime Estimate

The measured runtime for the lighting products during discharge in the first phase of testing was compared to the Fraunhofer ISE model runtime estimate. The deviation between the two is defined as a percent deviation from measured value of the Fraunhofer ISE model in comparison with measured experimental values (Equation 3).

$$\text{Percent Deviation} = \frac{\text{Actual Runtime} - \text{Estimated Runtime}}{\text{Actual}} \qquad \text{Equation 3}$$

where,

Actual Runtime is the measured runtime of the lighting product after one day of charge

Estimated Runtime is the estimate of the SRT for the lighting product from the Fraunhofer ISE model

The comparisons between the actual and estimated runtimes of the seven products are plotted in a graph for comparison (Figure 12). Negative values of percent deviations from measured value indicate an overestimate of the product SRT from the Fraunhofer ISE model and positive values indicate an underestimate. A range of sun hours were witnessed during the charging cycles in the outdoor testing phase (around 1 to 5 W/m^2/day). It was found that there is a large deviations from measured value in the Fraunhofer ISE estimate of the SRT for several of the products tested (Table 3). Some of the products showed both positive and negative deviations from measured value. Five out of the seven products tested had a deviation from measured value of above 20%. In addition, there was no clear trend between the deviations from measured value in SRT estimates and the range of sun hours in which the lighting products were tested.

Table 3: Summary of the SRT from outdoor measurements and Fraunhofer ISE estimates for solar resource above 4.5 kWh/m^2/day.

Product	Sun Hours (kWh/m^2/day)	Measured SRT (hrs)	Fraunhofer ISE Estimated SRT (hrs)	SRT Percent Deviation (Measured vs Estimated)
Product 1	4.7	1.9	2.2	-19%
	4.7	2.1	2.2	-7%
	4.9	1.7	2.3	-38%
	5.4	2.2	2.5	-16%
	5.5	2.5	2.6	-3%
Product 2	4.6	3.4	10.0	-192%
	4.7	1.3	10.0	-681%
	4.9	2.7	10.0	-275%
	5.3	2.6	10.0	-285%
	5.4	2.0	10.0	-393%
	5.5	3.6	10.0	-179%
Product 3	4.7	3.8	4.3	-12%
	4.7	3.4	4.2	-22%
	4.9	4.2	4.5	-8%
	5.2	4.3	4.7	-10%
	5.4	3.9	4.8	-22%
	5.5	4.1	4.9	-20%
Product 4	4.7	5.1	4.0	21%
	5.3	6.0	4.5	25%
	5.4	5.7	4.6	20%
	5.5	5.5	4.7	15%
Product 5	4.7	3.6	5.1	-42%
	5.3	5.6	5.1	8%
	5.4	5.5	5.1	7%
Product 6	5.3	9.8	8.0	19%
	5.4	9.4	8.2	13%
	5.4	9.4	8.2	13%
	5.5	9.7	8.4	13%
Product 7	5.3	3.0	3.4	-13%
	5.4	3.4	3.5	-2%
	5.4	2.9	3.5	-20%
	5.5	3.7	3.6	1%

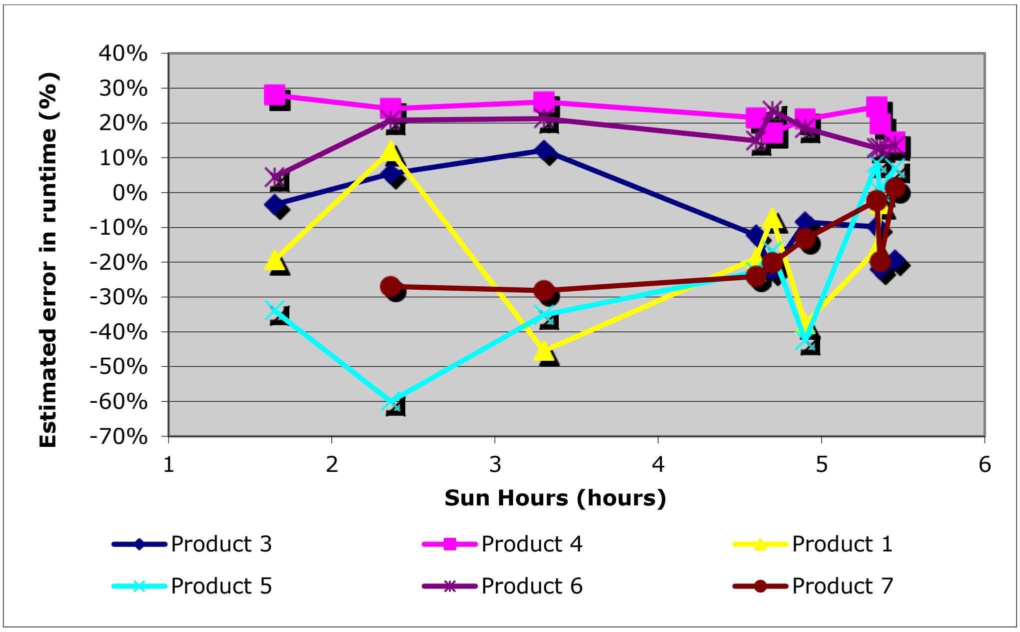


Figure 12: Percent deviation from the measured value in the Fraunhofer ISE estimate of runtime for the seven products tested. Each of the data points indicates the deviation from the measured value in SRT estimate for each charge/discharge cycle.

Product 2 had by far the greatest deviations from measured value in the estimate of runtime from the products tested (-100% to -600%).[11] The deviations from measured value in runtime estimate of Product 5 and Product 1 lighting products showed a large variation over the sun hours tested and had both positive and negative SRT estimates. For Product 5 the deviations from measured value ranges from -60% to +10% and for Product 1 this deviation from measured value ranges from -45% to +10%. Product 6 and Product 4 show a relatively constant deviation from measured value in estimate that hovers just around the +20% mark. Product 3 has both positive and negative deviations from measured value in estimates ranging from -20% to

[11] The percent deviation from the measured value for the runtime estimate of Product 2 is very large (-100% to -600%) and hence not included in Figure 12).

+10%. Refer to Table 4 for the average deviations from measured value and standard deviations of the average in SRT estimate for each of the products tested.

The large variability in predicting the SRT for the products tested indicates that the Fraunhofer ISE model for estimating the SRT for the products tested is inaccurate. Further analysis was conducted in order to determine the main sources of the deviations from measured value in the Fraunhofer ISE model.

5.2 Component Level Performance

The current and voltage to the lighting product battery and the solar resource was monitored during solar charge cycle in the first phase of testing. Similarly the current and voltage from the battery to the lamp of the lighting product was monitored during the discharge cycles. These measurements enabled the tracking of energy from the PV module into the product battery and finally from the battery into the lamp of the lighting product. On the basis of the energy flows within the product component level performance factors (component efficiency) were analyzed for each of the products. The measured component efficiencies for each of the products were compared to the empirical values used in the Fraunhofer ISE model to determine the source of inaccuracy in the model.

The component efficiencies for all the products are coupled into two parts, battery efficiency and a combined value for the PV_{mpp} and electronics efficiency. These factors are graphed against the sun hours for each charge/discharge cycle to compare the performance factors of different products (Figure 13 and Figure 14)

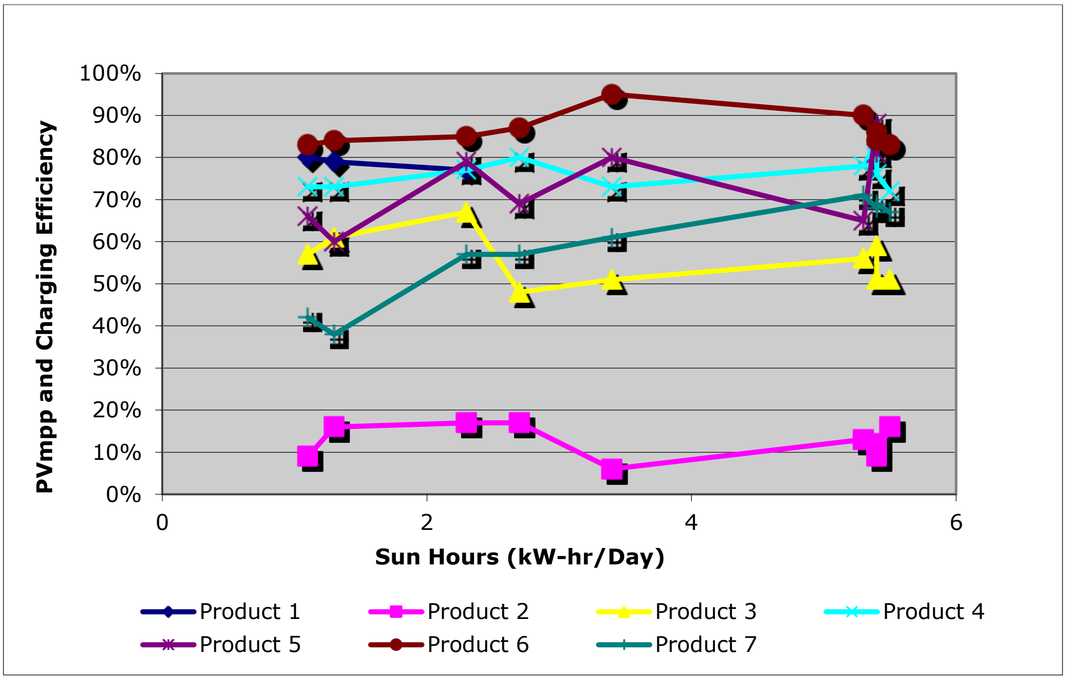


Figure 13: Combined PV_{mpp} and electronics efficiency of products for each charge cycle. Each of the points represents the average PV_{mpp} and electronics efficiency over the entire charge cycle.[12]

The Fraunhofer ISE model uses a single value for the PV_{mpp} and charging efficiency (Charging performance = 86% and PV_{mpp}=80%) that is independent of the type of PV module or charging electronics used in the lighting product. This gives a combined PV_{mpp} and charging efficiency value of 69% for all solar charged off-grid lighting products. This combined efficiency value differed greatly from some of the observed efficiency values for all the products tested, which ranged from about 10% for Product 2 and up to 90% for Product 6. This discrepancy is one of the reasons why the Fraunhofer ISE model is inaccurate.

[12] Product 1 has only three measured data points as data for current and voltage during the charge cycle was not collected for the first few cycles of the test phase.

Another factor that influenced the large spread of the deviations from meadured value observed in the Fraunhofer ISE model for SRT estimation is that the model assumes a linear behavior between the solar resource and the SRT for a lighting product. However, experimental data shows that cycle efficiency values in fact vary from one charge cycle to another suggesting non-linear behavior for the components within a lighting product. These variations can be attributed to the dynamic interaction among the solar resource, the operating point of the PV module, battery state of charge and the electronics of the lighting product.

Among all the products tested, Product 2 has the lowest electronics and PV_{mpp} efficiency (8 to 18%) and also the greatest deviation from the Fraunhofer ISE estimate.[13] This is one of the major reasons that the Fraunhofer ISE model gave large over estimates for the SRT of Product 2. Similarly, Product 5 shows a highly variable PV_{mpp} and electronics efficiency (65 to 85%) over the charge cycles tested. This characteristic makes it difficult to predict the SRT of a lighting product from the linear Fraunhofer ISE model.

Product 7 has a lower PV_{mpp} and electronics efficiency at low sun hours (1-1.5 kWh/m^2-day) but steadies between 60 to 70% for mid to high range of sun hours (2 to 5.5 kWh/m^2-day). Similarly, the PV_{mpp} and electronics efficiency for Product 3 steadies to 50 to 60% for mid to high range of sun hours. The PV_{mpp} and electronics efficiency of Product 4 and Product 5 are generally steady at 85% and 75% respectively for the range of sun hours tested. For these products it is possible to get

[13] This can be largely attributed to the electronic circuit of the product, which uses a resister to control the current into the battery causing higher losses in the charge cycle.

a good SRT estimate from the Fraunhofer ISE model provided the estimates for the component efficiencies are closer to the experimental values.

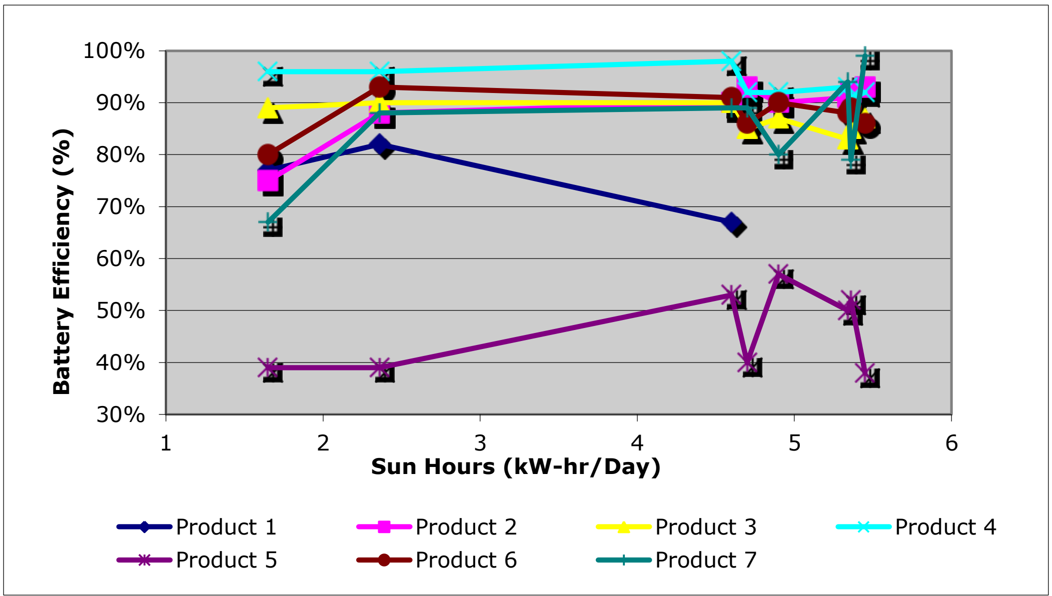


Figure 14: Battery efficiency of products for each charge cycle. Each of the points represents the average battery efficiency over the entire charge cycle

The second component efficiency analyzed was the battery efficiency of the lighting products. The battery efficiency of the lighting products tested remained relatively constant for most of the products over the range of sun hours. Battery storage efficiency observed varied from 40% (for Product 5) up to 95% for Product 4. The Fraunhofer ISE model uses empirical battery performance factors based on the battery chemistry of a lighting product. The model estimate for SLA and Li-ion battery storage efficiency is 90% and estimates for NiMH and NiCd are 75%. The Fraunhofer ISE model estimates for SLA and Li-ion batteries were consistent when compared to experimental results. However the model underestimated the storage efficiency of NiMH batteries by around 15% for the products tested.

Product 3 and Product 7 use SLA batteries (6V), which give a performance factor of 80 to 90%. These values are close to the Fraunhofer ISE model estimate for SLA batteries. Product 6 uses a Li-ion battery, which also gives a performance factor similar to the Fraunhofer ISE estimate of 90%. Product 2 and Product 4 have NiMH batteries and have a performance factor close to 90%, which is greater by 15% than the Fraunhofer ISE estimate for the same.

Product 5 uses a NiCd battery, which gives an unsteady performance factor varying between 40 to 60% over the sun hours tested. This value is also much lower than the other products tested. The reason for the variability in the battery performance of Product 5 is unclear. However, the variation in the battery performance will make it difficult to predict the SRT of this product with a proportional model.

5.3 Revision Testing

In order to develop a method to achieve more accurate estimates for the PV_{mpp} and electronics efficiency, the real time charge efficiency within a charge cycle was analyzed for the lighting products on a clear sunny day (Figure 15). The analysis showed that for some of the products the component efficiencies during the entire day remained relatively constant (e.g. Product 2 and Product 6). One notable exception to this is the Product 3 that has a relatively constant PV_{mpp} and electronics efficiency during the bulk charging phase and then drops towards the end of the charge cycle. This drop is presumably due to the conditioning characteristics of the electronics that reduces the charge from the PV module, as the battery comes close to the full capacity at the end of the charge cycle.

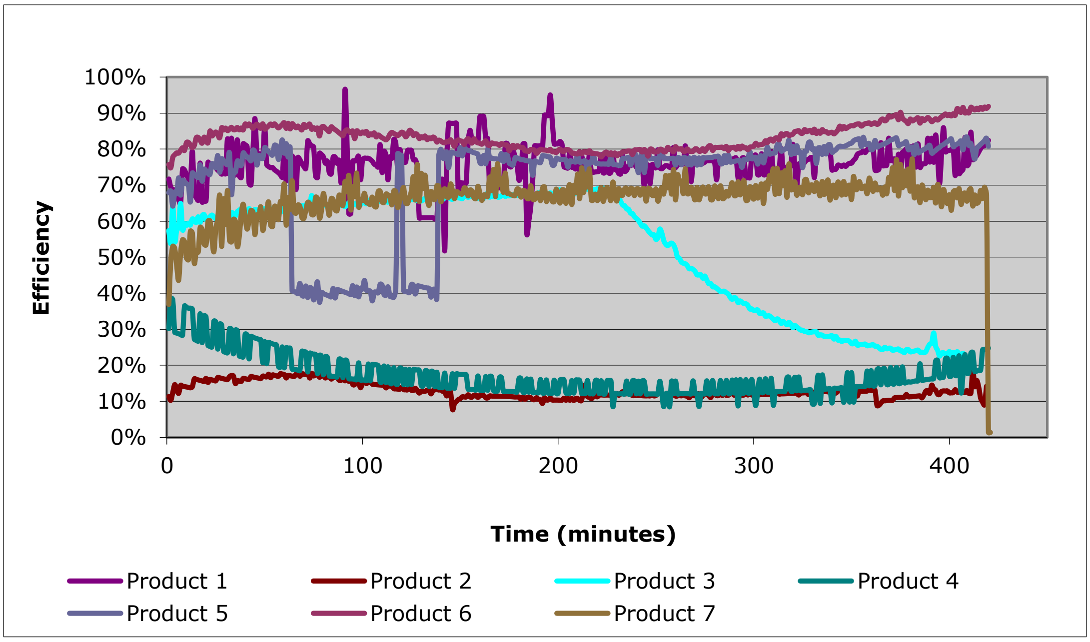


Figure 15: Figure shows the real time PV_{mpp} and Electronics efficiency of the seven products during the charge cycle. A clear sunny day was chosen for analyzing the component efficiencies of the products.

Although there was a variation in the charging efficiency for some of the lighting products tested, the efficiency values remained relatively constant during the bulk charging part of the charge cycle. Hence it was decided that single point efficiency measurements in the middle of the charge cycle could help reduce the inaccuracies observed in the Fraunhofer ISE model by adequately reflecting the average charge cycle efficiency. Furthermore, these single point efficiency measurements would require little additional cost to the LAQTM in terms of personnel, equipment and product test time. The revised Fraunhofer ISE model was compared to the original along with the Abbreviated PV GAP method to evaluate the accuracy of each method (Figure 16). The following sub sections discuss the performance of each of the methods used in estimating SRT.

5.3.1 Average Cycle Efficiency

Applying the actual average cycle efficiency to the Fraunhofer ISE model gives a baseline to compare the original and revised method for estimating SRT. Predictably, by applying the average cycle efficiencies to the Fraunhofer ISE model, there was an improvement in the predictability of the SRT for all of the lighting products used in the study (Figure 16).[14] The greatest improvement in solar runtime estimate is for Product 2 mainly due to the better estimate of the electronics efficiency. However, the confidence interval of the average deviation for Product 2 was greater than 20% in both the positive and negative direction. Overall with the average cycle efficiency values, five of the six products showed a deviation from measured value in SRT estimates of less than 20% as compared to the measured values. This indicates that with better estimates for the component efficiencies in the Fraunhofer ISE model, it is possible to reduce most of the inconsistencies in estimating SRT for lighting products.

5.3.2 Revision: Single Point Efficiency

When compared to the Fraunhofer ISE model, the single point efficiency method gave improved results for all of the seven products tested. As with the

[14] During the test cycle, Product 1 current and voltage values were measured for only three of the nine cycles. Hence the average values were not used for calculating the overall performance coefficient and SRT for this product.

previous revision, better estimate of electronics efficiency for Product 2 vastly improved the solar runtime estimate when compared to the Fraunhofer ISE Model. However, the average deviation from measured value for Product 2 was still high at 50% and had a large spread (-15% to -90%). Product 5 and Product 1 showed an underestimate and overestimate close to 30%, respectively. Overall, four of the seven lighting products tested have a deviation from measured value of below 20%.

5.3.3 Abbreviated PV GAP

The Abbreviated PV GAP method gave better results for five of the six products tested when compared to the Fraunhofer ISE. Three of the six products have a solar runtime estimate with deviations from the measured value of less than 20%. This method gives better results for Product 3, Product 2 and Product 1 when compared to the revised Fraunhofer ISE model. The F statistical analysis shows that the Abbreviated PV GAP method is marginally more accurate than the revised Fraunhofer ISE method. Overall the 12-hour cycle of the Abbreviated PV GAP method for determining the solar runtime is very accurate for some products (e.g. Product 1, Product 3, and Product 6) but is not good at predicting the results for others (e.g. Product 4, and Product 5).

One reason for the deviations from the measured value in the Abbreviated PV GAP method could be that the operating points observed during the solar charge cycles were different than those provided by the power supply in the Abbreviated PV GAP charge cycle. This will cause the components in the lighting product to act differently in the two methods. Analysis of the operating points for Product 4 during the Abbreviated PV GAP charge cycle shows that there are differences in the power supply operating points and the PV module operating points during a charge cycle (Figure 17). The Abbreviated PV GAP method used in this analysis represents a charge cycle for a clear sunny day (i.e. 5 kWh/m^2-day). However, the operating points for the charge cycle are different than the output given from the PV module of the product from the IV curve test. The Abbreviated PV GAP operating power points tend to be lower than the maximum operating power point from the IV curve at different solar radiation levels. Additionally, there is no charge period in the Abbreviated PV GAP method that simulates a solar resource above 700 W/m^2, which is routinely observed on a clear sunny day in Arcata, California. This could be another reason why the Abbreviated PV GAP method could not estimate the SRT accurately for Product 4.

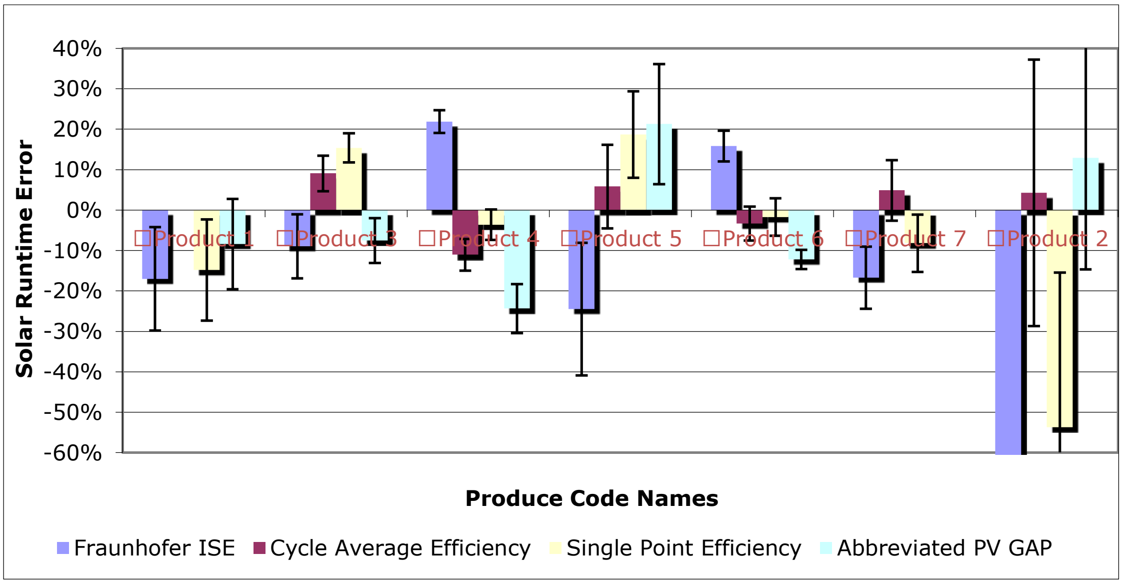


Figure 16: Deviations from measured value in solar runtime estimates for different revisions. Each bar indicates the average deviation (of the outdoor charge-discharge cycles) in SRT estimates for the different methods and the line on the bar indicates the range of deviation from the average.

Table 4: Summary results for range of deviation from the measured value in solar runtime estimates for all revisions (values in percentage).

Product Code Name	Fraunhofer ISE Method	Using Average Cycle Efficiency	Using Single Point Efficiency	Abbreviated PV GAP Method
	Range for Percent Deviation from the Measured Value (95% confidence interval)			
Product 1	-29.8 to -4.3	-58 to -11[15]	-27 to -2	-20 to 3
Product 2	-470 to -243	-29 to 37	-92 to -16	-14 to 41
Product 3	-17 to -1	5 to 14	12 to 19	-13 to -2
Product 4	19 to 25	-15 to -7	-7 to 0	-30 to -18
Product 5	-40.9 to -8.1	-5 to 16	-8 to -29	6 to 36
Product 6	12 to 20	-7.5 to 1	-6 to 3	-15 to -10
Product 7	-24 to -9	-3 to 12	-15 to 1	-- [16]

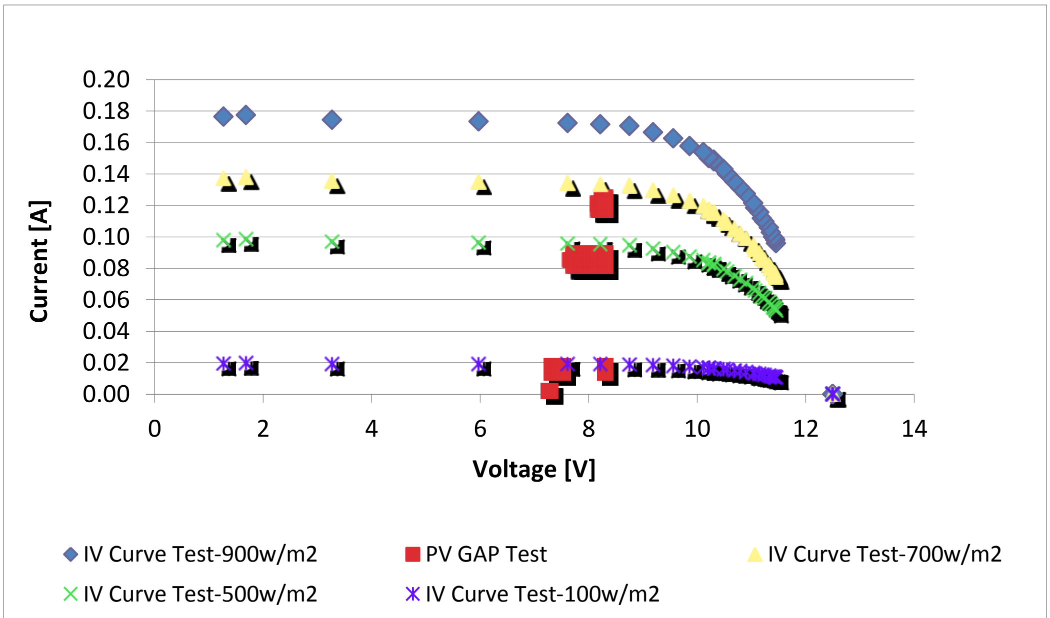


Figure 17: Comparison of the operating points in the Abbreviated PV GAP charge cycle and the PV module operating points from the IV curve test for Product 3.

[15] The range for HSI is based on only three cycles of charge-discharge since data for current and voltage was not collected for first five cycles.
[16] Revision-III does not include data from Product 7 since the product failed after Revision-I tests.

The main reasons for the improvement in the solar runtime estimate for the revised Fraunhofer ISE model are the better estimates for component efficiencies used in the estimation of SRT (Figure 18 and Figure 19). Single point measurements for the PV_{mpp} and electronics efficiency gives relatively accurate results compared to the Fraunhofer ISE model, for six of the seven lighting products tested. The main reason for improvement in the SRT estimate for Product 2 is the improvement in the estimates of the electronics efficiency. The average combined PV_{mpp} and electronics efficiency varied from 9 to 16% and the single point measurements gave an average value of 25%. This difference also explains some the deviation from measured value observed in estimating SRT with the revised Fraunhofer ISE model. The inherent limitation of the single point measurements for the PV_{mpp} and electronics efficiency is that it does not capture the variations over the entire charge cycle of the lighting product. Thus we see that the difference between the measured efficiencies from the outdoor runs and the single point measurement efficiencies are fairly significant in a number of cases (e.g. Product 2, Product 4 and Product 5). Product 5 showed a very low single point efficiency of around 35% as compared to the actual values of 60 to 90%. Reasons for this deviation were unknown. However, since the different tests were carried out over 18 months with the same product sample, there could have been wear on the components of the product that caused it to behave differently from one phase of testing to the next.

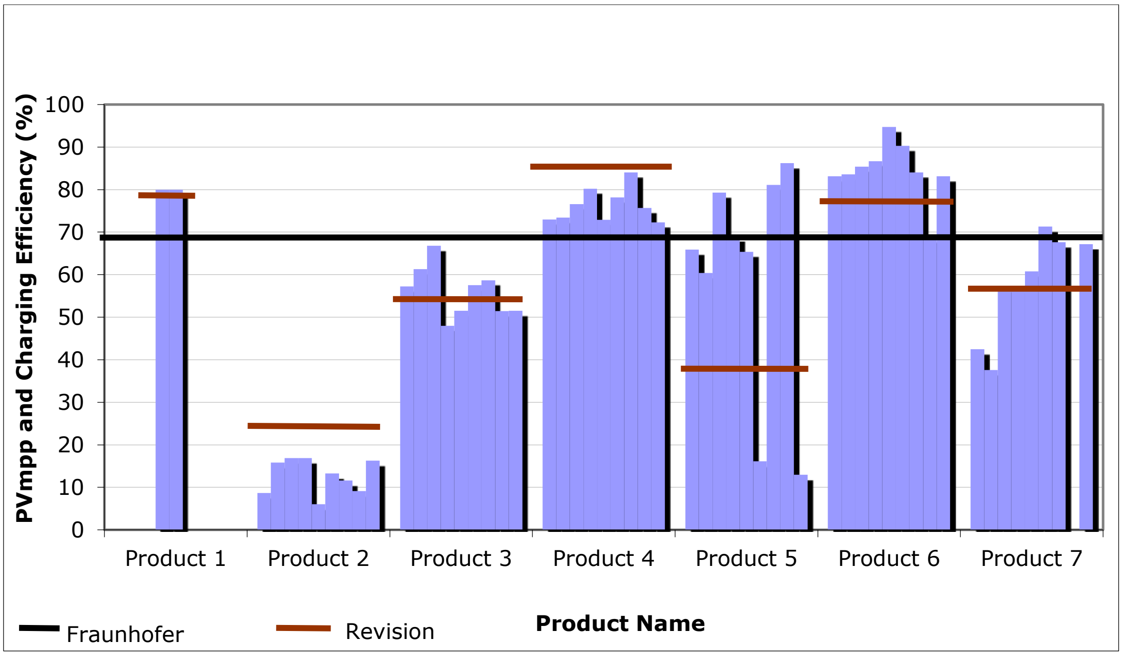


Figure 18: Comparison of actual and estimated values of combined PV_{mpp} and charging efficiency for the products tested. Each bar indicates the measured PV_{mpp} and electronics average cycle efficiency and the black and red lines indicate the Fraunhofer and single point estimates for the same, respectively.

The Fraunhofer ISE empirical estimates and revised estimates for battery storage efficiency were compared to the experimental values obtained during the solar charge/discharge cycles. Both the revised and original Fraunhofer ISE estimates for battery efficiency were generally close to each other. However for some of the products (e.g. Product 1, Product 4, Product 5), both these estimates varied significantly from the experimental battery efficiency values observed during the charge/discharge cycles. This variation can be attributed to the difference between the charge (current and voltage) seen by the product battery from the PV module and the Cadex battery analyzer during the charge cycle of the two methods. The result is a difference in different charge-discharge behavior of the lighting product battery.

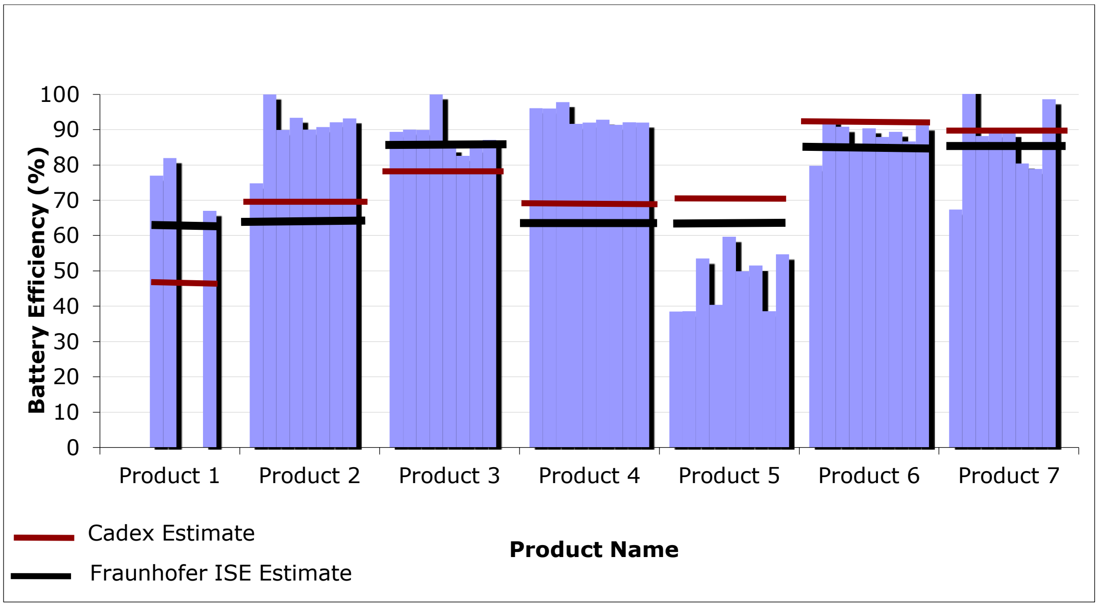


Figure 19: Comparison of actual and estimated value of battery efficiency for the products tested. Each bar indicates the actual battery storage efficiency during the charge-discharge cycle and the black and red lines indicate the Fraunhofer and revised estimates for the same, respectively.

6 FUTURE RESEARCH

The analysis in this study shows that the original Fraunhofer model for estimating SRT is inaccurate. The revised model and the Abbreviated PV GAP method provide more accurate ways for estimating SRT for lighting products. However, even these methods are not without deviation from measured value in estimating SRT. Products in this study like Product 2 and Product 5 still have deviations of greater than 20% in estimating SRT, which are over the acceptable limit for this parameter. Further research needs to be done in order reduce the deviation from measured value in estimating SRT for lighting products.

One of the areas of concern is that the single point measurements in the revised Fraunhofer ISE model may not be reflective of the average cycle efficiency during solar charge for some of the lighting products. This could be corrected by creating a new method that combines aspects of the Abbreviated PV GAP and revised Fraunhofer ISE methods for the six samples tested in the LAQTM. Under this scheme, the electronics efficiency would be measured over the entire charge cycle using the Abbreviated PV GAP method. The battery efficiency and PV_{mpp} efficiency would then be determined using the single point measurement methods developed in this study. These performance efficiencies would then be used in the revised Fraunhofer ISE model to estimate the SRT for a lighting product.

Further efforts need to be aimed at ensuring that the current and voltage values seen by different components of the lighting product the during the Abbreviated PV GAP charge cycle are close to the actual values observed during the solar charge cycle. A power supply and resistor circuit should be developed to ensure that the power supply simulates a particular PV module more accurately. The test method should be verified for repeatability of the results. Finally, a round of outdoor testing should be conducted to compare the final SRT test method with outdoor experimental results for verification.

7 CONCLUSION

- Experimental tests conducted with a variety of off-grid solar charged lighting products have shown that the Fraunhofer ISE method for estimating the SRT of the products tested is inaccurate. Compared to experimental results, the Fraunhofer ISE estimate deviates from the measured value by more than 20% for five of the seven products tested.

- One of the main reasons for the inaccuracy of the Fraunhofer ISE model is that the in built empirical estimates for component efficiencies of the lighting products are inaccurate. Additionally, the Fraunhofer ISE model for estimating SRT for a lighting product is a linear model whereas the response of the different components in the lighting product is nonlinear. This makes it difficult to predict the SRT for lighting products with the Fraunhofer ISE model.

- The revised Fraunhofer method uses single point efficiency measurements to get a more accurate estimate of the average component efficiencies during the charge cycle. This revision resulted in better estimates of SRT relative to the original Fraunhofer ISE method. However, even with the revised method, three of the seven products tested had SRT estimates that deviated from measured values by greater than 20 percent.

- Overall the 12-hour cycle of Abbreviated PV GAP method for determining the solar runtime is very accurate for some products but is not good at predicting the results for others. As compared to the revised Fraunhofer ISE method, the Abbreviated PV GAP method is marginally more accurate in estimating SRT. One reason for the deviations from the measured value in the Abbreviated PV GAP method could be that the operating points observed during the solar charge cycles were different than those provided by the power supply in the Abbreviated PV GAP charge cycle. The Abbreviated PV GAP operating power points tend to be lower than the maximum operating power point from the IV curve at different solar radiation levels. Additionally, there is no charge period in the Abbreviated PV GAP method that simulates a solar resource above 700 W/m^2, which is routinely observed on a clear sunny day in Arcata, California and many other locations. This could be another reason why the Abbreviated PV GAP method could not estimate the SRT accurately for some products.

- Future efforts are directed towards integrating the revised Fraunhofer ISE method and the Abbreviated PV GAP method for estimating SRT of solar charged off-grid lighting products. The electronics efficiency will be measured over the entire charge cycle using the Abbreviated PV GAP method. The battery efficiency and PV_{mpp} efficiency will be determined using the single point measurement methods developed in this study. These performance efficiencies will then be used in the revised Fraunhofer ISE model to estimate the SRT for a lighting product.

- This study has identified a framework to incorporate accessory charging features of lighting products in the Fraunhofer ISE model in order to capture how mobile phone charging affects the daily operating time. Future efforts will be directed at verifying this new framework for calculating daily operating time.

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9 APPENDIX A: EXPERIMENTAL SETUP AND EQUIPMENT SPECIFICATIONS

More information about the equipment used in the experiments conducted during the course of this study is detailed in this appendix. Figure A20 shows a sample product in the dark box and

Table A5 gives details about the equipment used to measure the different parameters during the testing phase.

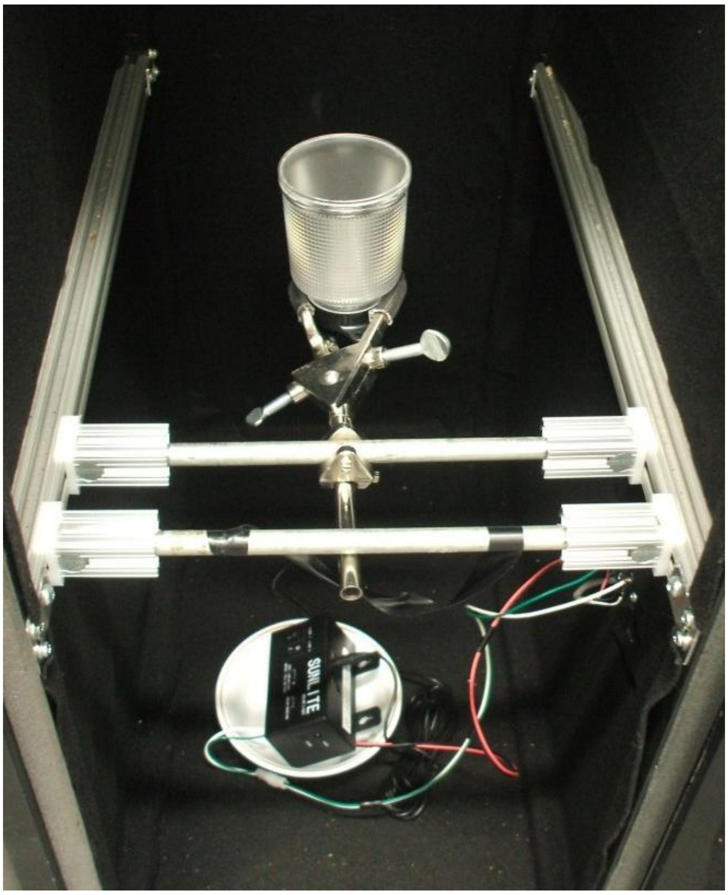

Figure A20: Picture of the dark box setup used while discharging the lighting product (see sample product in picture). A light meter placed directly above measures the light output (in lux) of the lamp at a distance of one meter. Additionally, current and voltage measurements are made during the lamp discharge using a transducer and voltage divider built in to the dark box setup.

Table A5: Equipment used for out-door testing of lighting products

Equipment	Model#	Measured Parameter	Precision/Accuracy
Pyranometer	EPPLEY PSP Radiometer	Global Solar Radiation (in plane of lighting product PV panel)	Sensitivity approximately 9 microvolts per W/m^2
Fluke Multimeter	Fluke 287 True RMS Multimeter	Voltage from the EPPLEY PSP Radiometer	Range and Resolution 50.000 mV,500.00 mV, 5.0000 V, 50.000 V, 500.00 V, 1000.0 V Basic Accuracy 0.025 % 0.4 % (true-rms)
Current Transducer	CR Magnetics DC current transducer CR 5210-2	Current into and out of components of the lighting product (PV module, electronics and battery)	accuracy +/-1.0%; output signal 0.5 VDC
Voltage Divider	Isolated V input 5B31 analog devices	Voltage from components of the lighting product (PV module, electronics and battery)	Range ±1 V to ±20 V
Data logger	Onset Hobo Data Logger	Voltage/Current into and out of components of the lighting product (PV module, electronics and battery)	Range: 0 to 2.5 VDC Accuracy: ± 2 mV ± 2.5% of absolute reading
Light meter	Extech 401036 Data Logging Light Meter	Light output (in Lux) of the lighting product lamp during discharge cycle	Specifications: Light Intensity Range 0-20 (Lux/Fc) Resolution and Accuracy of 0.01 ±(3% reading + 5 digits) Also has Light Intensity/Range 0-200 0.1 0-2,000 1 0-20,000 10

10 APPENDIX B: TEST METHODS

This section details the test methods used in this study for estimating the Solar Runtime of an off-grid lighting product. The Lighting Africa Quality Assurance Team developed these methods in the year 2011-2012. Parts of the test methods have been adapted from the Lighting Africa Quality Test Method, Test Procedure version – 2.01. Formatting for the test methods is adapted for this study but some of the formatting has been left unchanged from the original document.

The test methods described in this section are Solar Runtime Calculation, lighting product electronics efficiency test, PV panel maximum power point efficiency test, Battery efficiency test, Solar Runtime Calculation with mobile phone charging and lighting product electronics efficiency test with mobile charging.

10.1 Solar Runtime Calculation

10.1.1 Scope

Daily solar runtime calculation is a model for prediction of the daily runtime of a solar off-grid lighting product given a certain amount of sun hours in the day.

10.1.2 Background

An important parameter in understanding the performance of a solar lighting product is the daily solar runtime of a product i.e. the amount of hours the lighting product will run given that the product is charged in the day for a particular amount of sun hours. This is parameter gives an indication of how a product may perform on a daily basis in the field.

The efficiency of various components (PV module, battery and electronics) in the lighting product determines what fraction of the incident energy is stored and used to run the light source. The solar runtime calculation model combines these efficiencies to determine the hours of operation of a lighting product in the night. Fraunhofer model for calculation the solar runtime of a product uses empirically determined values for PV maximum power point (PV_{mpp}) efficiency, charging and battery efficiency for lighting products.

10.1.3 Test Outcomes

List all outcomes from module in table, with examples below:

ID	Metric	Reporting Units	Note
LAQTM.	Solar Runtime	Hours	Calculation Model

10.1.4 Related Tests

The electronics efficiency test, PV_{mpp} test and battery efficiency test are inputs to the Solar Runtime Calculation of a lighting product. This module also draws from the battery capacity test and IV curve test for calculating solar runtime of the product.

10.1.5 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.1.6 Internationally Recognized Test Method

Refer to commercially available simulation tools like PV Sol, PV Syst, Homer and others.

10.1.7 Equipment Requirements

- List equipment here.

10.1.8 Procedure

10.1.9 Lighting Africa Recognized Test Method

10.1.9.1 Method 1 Solar Runtime Calculation

A special tool based on an Excel sheet was developed to perform these calculations easily.

A standard solar day is typically defined as 5,000 Wh/m^{2}day, and should be used to estimate the run time. Irradiance values other than 5,000 Wh/ m^{2}day can also be used with the tool for location-specific estimates. With the help of PV simulation software, the following irradiation values were calculated for a standard day for the countries examined in Sub-Saharan Africa:

Ethiopia [Addis Abeba]: 5,194 Wh/m ²d

Ghana [Accra]: 4,912 Wh/m ²d

Kenya [Nairobi]: 5,382 Wh/m ²d

Zambia [Lusaka]: 5,170 Wh/m ²d

Tanzania [Dodoma]: 5,618 Wh/m ²d

The average irradiation is 5,255 Wh/m²-day.

Since many countries in Sub-Saharan Africa are located in proximity of the equator, an inclination angle of 0° is acceptable. Furthermore, no shading losses are assumed.

10.1.9.1.1 Equipment Requirements

- N.A.

10.1.9.1.2 Test Prerequisites

Following tests must be completed before the solar runtime calculation

- The Battery Capacity Test using Cadex battery analyzer
- IV curve test with the IV curve tester
- Autonomous Runtime test
- Electronics efficiency test
- Battery Efficiency calculation
- PV panel maximum power point (PV_{mpp}) efficiency test

10.1.9.1.3 Apparatus

N.A.

10.1.9.1.4 Procedure

Screen Shot of the Excel Tool

Solar Run Time Calculation		Notes
Method	LAQT 2.0 *based on model by FISE*	
Test Conducted by	BM	**Fill out Green boxes for Input**
Date	16-11-2100	**Read output from yellow boxes**
Location	SERC	
Sample ID Code:		
CALCULATION INPUTS		
Battery Type	Lead-Acid	<- Choose type from pull-down
Battery Voltage [V]	6	
Battery Capacity [mAh]	5120	
Autonomous Time [h]	10.2	
PV Power [W]	12.4	
CALCULATION RESULTS		
Daily Solar Run Time [h]	10.2	
Percent of a full battery charge received from solar day	100%	
CALCULATION ASSUMPTIONS AND CORRECTION FACTORS		
Solar Day Energy (number of full sun-hours) [kWh/m2-day]	5	<- 5 kWh/m2 is the standard day
Electronics Efficiency [%]	0.84	
Battery Efficiency [%]	0.86	
PV MPP Losses [%]	0.84	
Correction Factor [%]	0.61	
PV Energy [Wh]	62	
Available Energy [Wh]	38	

Figure B21: Screenshot of the Excel Tool for calculating the daily solar run time with example inputs.

Equations employed by the Excel tool are documented in the calculations section.

How to use the tool:

- Input test –related information in the green boxes.
- In Calculation assumptions and correction factors section input values from electronics efficiency test, PV_{mpp} test and battery efficiency test.
- Input characteristics of the battery, PV module, and autonomous run time in the green boxes in the "Calculation Inputs" section. Note that there is a drop-down selection box for battery type (chemistry).
- Read the results from the "Calculation Results" section.

10.1.9.1.5 Calculations

- Calculate lighting product correction factor

(Correction Factor)=(Battery Efficiency*Electronics Efficiency*PVmpp Efficiency)

The electronics efficiency test, PV_{mpp} test and battery efficiency test values are substituted for this calculation

- Calculate energy from PV module to the battery of lighting product

(PV Energy)=(Solar Day Energy*Correction Factor*PV Power)

Where,

PV Energy (W-hr)= Energy delivered to battery from PV module

Solar Day Energy (Wh/m^2-day)= Energy from the sun in a day

PV Power (W) = Product PV panel power from IV curve test

Correction Factor = Lighting product correction factor

- Calculate the fraction of charge received by product battery from Solar Day

$$\text{Charge Fraction of Battery Capacity}=\frac{\text{PV Energy}}{\text{Battery Energy}}$$

Where,

Battery Energy (Wh) = Battery capacity measured by Cadex during battery capacity test

PV Energy (Wh)= Energy delivered to battery from PV module

- Calculate Daily solar runtime for the lighting product

  Daily Solar Runtime=(Measured Autoruntime)*(Charge Fraction of Battery Capacity)

Where,

Measured Auto-runtime (h) = Product Auto-runtime test value

Charge Fraction of Battery Capacity = Fraction of charge received by product battery from Solar Day

10.1.10 Reporting

- Date(s) and location
- Product name/Product ID
- The battery chemistry and PV module type and the specified ratings.
- Solar Run-Time (SRT)
- Any other pertinent information or observations.

Table for example reporting

<table>
<tr><td>Test Start Date</td><td>YYYY</td><td>MM</td><td>DD</td></tr>
<tr><td>Test End Date</td><td>YYYY</td><td>MM</td><td>DD</td></tr>
<tr><td>Test Location</td><td colspan="3">text</td></tr>
<tr><td>Product Name/ID</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Battery Specifications</td><td>Chemistry</td><td>Nominal Voltage [V]</td><td>Capacity [mAh]</td></tr>
<tr><td></td><td>*</td><td>*</td></tr>
<tr><td rowspan="2">PV Module Specifications</td><td>Type</td><td colspan="2">Rating</td></tr>
<tr><td></td><td colspan="2"></td></tr>
<tr><td rowspan="4">Calculation Data</td><td colspan="2">Assumption</td><td>Value</td></tr>
<tr><td colspan="2">Sun Hours</td><td>5kWh/m^2-day</td></tr>
<tr><td colspan="2">Accessory charging During Night-time</td><td>Yes/No</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Solar Run-Time (SRT)</td><td colspan="3"></td></tr>
<tr><td>Comments</td><td colspan="3">text</td></tr>
</table>

10.2 Lighting Product Electronics Efficiency

10.2.1 Scope

The purpose of the electronics efficiency test is to provide a measure of the charge efficiencies for lighting product electronics. The electronics efficiency value is used in calculating the solar runtime of a lighting product. A number of single point measurements of current and voltage are made before and after the electronics to determine the charging efficiency. The electronics efficiency test method is detailed in this module.

10.2.2 Background

The efficiency of various components (PV module, battery and electronics) in the lighting product determines what fraction of the incident energy is stored and used to run the light source. Estimating the electronics efficiency of a product gives an estimate of the energy lost from the PV module in charging the battery. This value is then used as an input in the Solar Runtime Calculation of the lighting product.

A power supply is used to charge a lighting product battery and the current and voltage before and after the electronics is measured for a fixed period of time. The ration of the average power delivered from the electronics to the power from the power supply will give the efficiency of the electronics. The current and voltage of the power supply is set to the current and voltage values recorded in the PV_{mpp} test.

10.2.3 Test Outcomes

ID	Metric	Reporting Units	Note
LAQTM.	Generator to battery efficiency (η_{G2B})	Percentage	Measurements made when state of charge of battery is 50%

10.2.4 Related Tests

The electronics efficiency test, PV_{mpp} test and battery efficiency test are inputs to Module Solar Runtime Calculation of a lighting product. This module draws from PV_{mpp} test for the drive current and voltage.

10.2.5 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.2.6 Internationally Recognized Test Method

10.2.6.1 Equipment Requirements

- NA

10.2.6.2 Procedure

- NA

10.2.7 Lighting Africa Recognized Test Method

10.2.7.1 Electronics Efficiency Test

The current and voltage to and from the electronics is recorded at fifteen second intervals. The setup is left to stabilize for five minutes before any readings are recorded.

10.2.7.1.1 Equipment Requirements

- Adjustable Power Supply
- Multi-meter for voltage measurements
- Clamp meter (or multi-meter) for current measurements.

10.2.7.1.2 Test Prerequisites

The battery of the lighting product should be at a 50% state of charge for this test. Additionally, this test should be performed after the completion of the PV_{mpp} test since the current and voltage recorded from the PV module during the test is the input to the power supply for the electronics efficiency test.

10.2.7.1.3 Apparatus

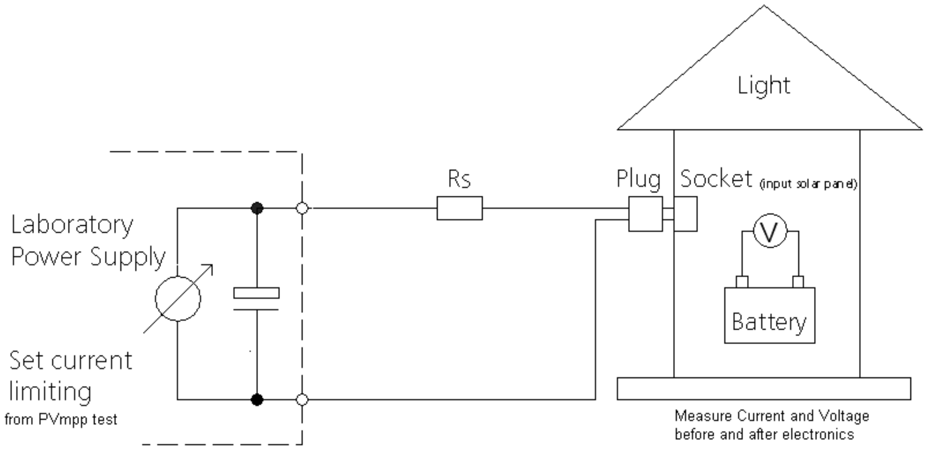

Figure B22: Sketch of the power supply and lighting product connection for electronics efficiency test

10.2.7.1.4 Procedure

- Charge the lighting product with a power supply for 5 minutes with current controlling. (Note: The current and voltage value should be input from PV_{mpp} test.)
- After 5 minutes of charging the lighting product battery from the power supply, measure the following four values:
    - Current going into the lighting product battery
    - Voltage across the lighting product battery
    - Current coming out of the power supply at the lighting product's power input socket
    - Voltage across the lighting product's power input socket

- Repeat taking these four measurements every 15 seconds over a minute. This provides a total of 4 readings for each of the four measurements.

10.2.7.1.5 Calculations

- Using the average values from the generator to battery efficiency data collection, determine the generator to battery efficiency (η_{G2B}) using the following equation:

$$\eta_{G2B} = \frac{\text{Energy into LP Battery}}{\text{Energy from Generator}} = \frac{I_B \times V_B}{I_{PS} \times V_{PS}}$$

Key,

η_{G2B} = Generator to battery efficiency
I_B = Averaged current into lighting product battery
V_B = Averaged voltage across lighting product battery
I_{PS} = Averaged current coming out of the power supply at the lighting product's power input socket
V_{PS} = Average voltage across the lighting product's power input socket

10.2.8 Reporting

Describe what the requirements are for a test report here:

- Report the following values.
    - Date(s) tested, and testing location, Tester name
    - The product sample number(s), and all equipment specifications and serial numbers.
- Drive current and voltage

- Waiting time

Table for example reporting

ID	Metric	Reporting Units	Note
LAQTM.	Generator to battery efficiency (η_{G2B})	Percentage	Measurements made when state of charge of battery is 50%

10.3 PV Maximum Power Point Efficiency (PV_{mpp}) Test

10.3.1 Scope

This module describes the test method for estimating the PV module maximum power point (PV_{mpp}) efficiency of a lighting product. The PV_{mpp} efficiency value is used in calculating the solar runtime of a lighting product.

10.3.2 Background

The efficiency of various components (PV module, battery and electronics) in the lighting product determines what fraction of the incident energy is stored and used to run the light source. The PV module operates at a power point that is generally lower than the maximum power point obtained from the IV curve test. This module describes a single point measurement to determine the PV_{mpp} efficiency value of the lighting product. This value is then used as an input in Solar Runtime Calculation of the lighting product.

The operating voltage of the lighting product PV module is found by measuring the panel voltage when connected to the lighting product on a clear sunny day. The comparison of the operating power with the product battery connected to the PV module to the maximum power point of the PV module will give the measure of the PV_{mpp} efficiency value for the lighting product.

10.3.3 Test Outcomes

ID	Metric	Reporting Units	Note
LAQTM.	PV_{mpp} Efficiency	Percentage	-

10.3.4 Related Tests

The electronics efficiency test, PV_{mpp} test and battery efficiency test are inputs to Solar Runtime Calculation of a lighting product. The operating voltage and current obtained from this module will be used as input to Electronics efficiency test.

10.3.5 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.3.6 Internationally Recognized Test Method

10.3.6.1 Equipment Requirements

10.3.6.2 Procedure

10.3.7 Lighting Africa Recognized Test Method

10.3.7.1 Method 1 PV Maximum Power Point efficiency test

A voltage reading is taken on a clear sunny day with the PV panel and the lighting product battery connected. Using a corresponding current value on the IV curve of the panel, the operating power point and maximum power point is compared to determine the PV_{mpp} efficiency of the module.

10.3.7.1.1 Equipment Requirements

- IV curve test rack[17]
- Pyranometer
- Multimeter
- Surface thermocouple and thermocouple reader

10.3.7.1.2 Test Prerequisites

- Outdoor measurements should be done on a clear sunny day and close to solar noon (± 2 hours or AM≤2).
- This test must be conducted after the PV module IV curve test
- This test must be conducted after the lighting product Autonomous Run-Time test

10.3.7.1.3 Apparatus

10.3.7.1.4 Procedure

[17] The IV curve test requires a test rack that enables the placement of the pyranometer and PV module in the same plane and normal to the sun.

- Use the Cadex battery analyser or similar equipment to bring the lighting product battery to 50% state of charge.
- Mount the PV module and pyranometer on the test rack normal to the sun (can use IV curve test rack). The PV module should be in the sun for twenty minutes before starting the test so that it reaches equilibrium temperature. Test for equilibrium by mounting a surface thermocouple behind the PV module. Equilibrium temperature can be reached by keeping a PV module in the sun for 20 minutes or having a less than 1°C rise of module temperature in one minute, which ever takes less time.
- Connect the lighting product to the PV module through the charging socket and measure the voltage across the PV module terminals.
- Note down the temperature of the PV module and solar radiation from the pyranometer.

10.3.7.1.5 Calculations

- Standardize the voltage reading
- Calculate the voltage correction factor

$$V_{cf} = 1 + T_v (T_{stc} - T_p)$$

Where,

V_{cf} = Voltage correction factor

T_v = Voltage temperature correction factor (refer to LA-QTM IV curve test for value)

T_{stc} = Temperature under standard test conditions

T_p = Measured PV module temperature during test

- Calculate Standardized Voltage

$$V_{std} = V_{cf} * V_{measured}$$

Where,

$V_{measured}$ = Voltage measured during the PV_{mpp} test

V_{std} = Temperature corrected voltage of PV module during PV_{mpp} test

- Find the operating power point of the PV module from the IV curve of the lighting product.
- Place the standardized voltage (V_{std}) on the IV curve of the product and note the corresponding current.
- Product of the standardized voltage (V_{std}) and current will give the operating power point ($P_{measured}$) of the PV module.
- Calculate the PV_{mpp} efficiency.

$$PV_{mpp} Efficiency = \frac{P_{measured}}{P_{mpp}}$$

Where,

$P_{measured}$ = Operating power point of the PV module obtained from

P_{mpp} = Maximum power point of lighting product PV module from IV curve test

10.3.8 Reporting

- Date(s) tested, and testing location
- Product name/Product ID
- The battery chemistry, PV module type and capacity ratings for the same.
- PV_{mpp} loss factor
- Any other pertinent information or observations.

Table for example reporting

Test Start Date	YYYY	MM	DD
Test End Date	YYYY	MM	DD
Test Location	text		
Product Name/ID			
Battery Specifications	Chemistry	Nominal Voltage [V]	Capacity [mAh]
		*	*
PV Module Specifications	Type	Rating	
PV module maximum power point (P_{mpp})			
PV module operating power point ($P_{measured}$)			
PV_{mpp} Loss Factor			
Comments	text		

10.4 Battery Efficiency Calculation

10.4.1 Scope

This module describes the calculation of battery storage efficiency of the lighting product. The efficiency value is calculated from the battery capacity test data

10.4.2 Background

The efficiency of various components (PV module, battery and electronics) in the lighting product determines what fraction of the incident energy is stored and used to run the light source. The battery efficiency test calculation gives an estimate of the storage efficiency of the lighting product battery. This value is then used as an input in Solar Runtime Calculation of the lighting product.

The data from the battery capacity test is analyzed for the last charge discharge cycle. The ratio of the energy output from the battery to the energy input to it gives the storage efficiency of the battery.

10.4.3 Test Outcomes

ID	Metric	Reporting Units	Note
LAQTM.	Battery Capacity	mAh	-
LAQTM.	Battery Storage Efficiency	Percentage	At least two complete charge discharge cycles is required for the calculation

10.4.4 Related Tests

The electronics efficiency test, PV_{mpp} test and battery efficiency test are inputs to Solar Runtime Calculation of a lighting product. This module draws from battery capacity test for the data to calculate the storage efficiency of the battery.

10.4.5 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.4.6 Internationally Recognized Test Method

10.4.6.1 Equipment Requirements

- List equipment here.

10.4.6.2 Procedure

10.4.7 Lighting Africa Recognized Test Method

10.4.7.1 Method 1 Battery Efficiency Calculation

10.4.7.1.1 Equipment Requirements

N.A

10.4.7.1.2 Test Prerequisites

Battery capacity test should be completed before this calculation

10.4.7.1.3 Apparatus

N.A

10.4.7.1.4 Procedure

The last charge-discharge cycle of the battery capacity test should be analyzed for this calculation

10.4.7.1.5 Calculations

- Calculate the total energy input into the battery of the lighting product during the charge cycle of the test. The current and voltage values used for this calculation should be from the last charge cycle after the prime and first discharge cycle.

$$E_{Charge} = \sum(V_{Charge} * I_{Charge})$$

Where,

E_{Charge} = Energy input to the battery during charge cycle

V_{Charge}= Voltage recorded during charge cycle

I_{Charge}= Current recorded during charge cycle

- Calculate the total energy output from the battery of the lighting product during the discharge cycle. The current and voltage values used in this calculation should be from the discharge cycle immediately after the charge cycle referred above

$$E_{Discharge} = \sum(V_{Discharge} * I_{Discharge})$$

Where,

$E_{Discharge}$ = Energy input to the battery during charge cycle

$V_{Discharge}$= Voltage recorded during charge cycle

$I_{Discharge}$= Current recorded during charge cycle

- Calculate the battery efficiency of the lighting product

$$h_{Batt} = \frac{E_{Discharge}}{E_{Charge}}$$

Where,

η_{Batt}= Battery efficiency of the lighting product

10.4.8 Reporting

Describe what the requirements are for a test report here:

- Date(s) and location

- Product name/Product ID
- The battery chemistry and PV panel type and the specified ratings.
- Battery Efficiency of the lighting product
- Any other pertinent information or observations.

Table for example reporting

<table>
<tr><td>Test Date</td><td>YYYY</td><td>MM</td><td>DD</td></tr>
<tr><td>Test Location</td><td colspan="3">text</td></tr>
<tr><td>Product Name/ID</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Battery Specifications</td><td>Chemistry</td><td>Nominal Voltage [V]</td><td>Capacity [mAh]</td></tr>
<tr><td></td><td>*</td><td>*</td></tr>
<tr><td>Battery Efficiency</td><td colspan="3"></td></tr>
<tr><td>Comments</td><td colspan="3">text</td></tr>
</table>

10.5 Solar Runtime Calculation (SRT) with mobile phone charging

10.5.1 Scope

Daily solar runtime calculation is a model for prediction of the daily runtime of a solar off-grid lighting product given a certain amount of sun hours in the day. This module details the solar auto-runtime calculation for lighting products that have additional auxiliary charging for accessories along with the main lighting product e.g. mobile charging, radio etc.

10.5.2 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.5.3 Internationally Recognized Test Method

10.5.3.1 Equipment Requirements

10.5.3.2 Procedure

10.5.4 Lighting Africa Recognized Test Method

10.5.4.1 Method 1: Solar Runtime Calculation (SRT) with mobile phone charging

10.5.4.1.1 Test Prerequisites

- The Battery Capacity Test using Cadex battery analyzer
- IV curve test with the IV curve tester
- Autonomous Runtime test
- Electronics efficiency test
- Battery Efficiency calculation
- PV module maximum power point efficiency test.

10.5.4.1.2 Module Outcomes

- The output of this calculation will give the number of hours a lighting product will run for from the solar resource in a day.
- This module can also be used to see the affect of auxiliary charging on the solar runtime of the product.

10.5.4.1.3 SRT Calculation

- Quantify the energy required to fully charge the auxiliary device (in Watt-hours). This can be done by analyzing the battery of the auxiliary device or using the rated value on the battery.

- Assume that in a day 50% of the energy required to fully charge the auxiliary device is used for daily consumption. The PV module or battery of the lighting product will provide this auxiliary energy on a daily basis (E_{Aux}).

- Assume the fraction of the daily auxiliary energy received directly from the PV module (Alpha: α) to be 50%.[18] This means that auxiliary charging is split evenly during night and daytime. If the lighting product does not include auxiliary charging at night as a feature then assume α = 1 and if lighting product has no solar charging option for accessories assume α = 0. This is determined from the Electronics efficiency test.

- Calculate energy from the PV module to the auxiliary

$$E_{G2A} = E_{Aux} * \alpha$$

Where,

E_{G2A} = Energy from PV module to auxiliary

[18] The value of Alpha (α) is subjective and is related to the number of hours and time of use of the auxiliary device and the auxiliary charging behaviour of the consumer.

E_{Aux} = Daily energy required for charging the auxiliary

α = 0.5 = Fraction of the daily energy required for auxiliary charging that is supplied from the PV module of lighting product

- Calculate the loss in energy passing in the pathway between the PV module and auxiliary.

$$Loss_{G2A} = E_{G2A} * (1 - \eta_{G2A})$$

Where,

$Loss_{G2A}$ = Energy loss in the pathway between PV module and auxiliary

η_{G2A} = Electronics efficiency measurement for the pathway between PV module and auxiliary. This value is obtained from the Electronics Efficiency module.

- Calculate energy from the PV module to the battery

$$E_{G2B} = (E_{PV,act} - E_{G2A} - Loss_{G2A}) * \eta_{G2B}$$

Where,

E_{G2B} = Energy from PV module to battery of lighting product

$E_{PV,act}$ = Actual energy from the PV module

$$E_{PV,act} = E_{PV} * \eta_{MPP}$$

Where,

E_{PV} = Theoretical maximum energy delivered from the PV module using the available solar resource and PV module maximum power point value obtained from PV module IV curve test.

η_{MPP} = Maximum Power Point Efficiency of the PV module. Value obtained from the PV maximum power point losses module.

η_{G2B} = Electronics efficiency measurement for the pathway between PV module and battery of the lighting product. This value is obtained from the Electronics Efficiency module

- Calculate energy from the battery of the lighting product to the auxiliary.

$$E_{B2A} = E_{Aux} * (1 - \alpha)$$

Where,

E_{B2A} = Energy from battery of the lighting product to the auxiliary

E_{Aux} = daily energy required for charging the auxiliary

Alpha = α = Fraction of the daily energy required for auxiliary charging that is supplied from the PV module of lighting product

- Calculate the loss in energy passing in the pathway between the battery of the lighting product and auxiliary.

$$Loss_{B2A} = E_{B2A} * (1 - \eta_{B2A})$$

Where,

$Loss_{B2A}$ = Energy loss in the pathway between battery of lighting product and auxiliary

η_{B2A} = Electronics efficiency measure for the pathway between battery of lighting product and auxiliary. This value is obtained from the Electronics Efficiency module

- Calculate the energy from the battery to the lighting product.

$$E_{B2L} = E_{G2B} - Loss_{Batt} - E_{B2A} - Loss_{B2A}$$

Where,

E_{B2L} = Energy from battery to the lamp of the lighting product

$Loss_{Batt}$ = Energy lost in the battery charge discharge cycle

$$Loss_{Batt} = E_{G2B} * (1 - \eta_{Batt})$$

Where,

η_{Batt} = Battery efficiency measurement obtained from the Battery Efficiency calculation module

- Calculate the Solar runtime of the lighting product.

$$SRT=\frac{E_{B2L}}{P_{ART}}$$

Where,

SRT = Solar runtime of the lighting product

P_{ART} = Average power supplied to the lamp of the lighting product during the autonomous runtime test (50% of initial lumens)[19]

Discharge the battery at I_{10} until 1.80 V/cell.

10.5.5 Reporting

Report the following information.

- Date(s) and location
- Product name/Product ID
- The battery chemistry and PV module type and the specified ratings.
- Solar Run-Time (SRT)

[19] LAQTM procedure will need to be changed to include data logging of current and voltage during ART test. For lighting products with non linear ART discharge, P_{ART} will vary depending on the state of charge of the battery, hence affecting the solar runtime calculation.

- Any other pertinent information or observations.

Table for example reporting

Test Start Date	YYYY	MM	DD
Test End Date	YYYY	MM	DD
Test Location	text		
Product Name/ID			
Battery Specifications	Chemistry	Nominal Voltage [V]	Capacity [mAh]
		*	*
PV Module Specifications	Type	Rating	
Calculation Data	Assumption		Value
	Auxiliary Energy (E_{Aux})		*
	Sun Hours		5kWh/m^2-day
	Alpha		0.5/1.0/0.0
	Auxiliary charging During Night-time		Yes/No
	Auxiliary charging During Day-time		Yes/No
Solar Run-Time (SRT)			
Comments	text		

10.7 Electronics Efficiency Test for lighting products with mobile phone charging

10.7.1 Scope

This testing procedure provides information regarding the charge efficiencies for lighting product battery and auxiliary charging.

10.7.2 Equipment Requirements

- Battery Analyzer or a voltage-specified disconnect device
- Devices to log current data
- Devices to log voltage data

10.7.3 Laboratory Requirements

- Accreditation from [international organization / specification]; or
- Laboratory Accreditation waiver from Lighting Africa

10.7.4 Internationally Recognized Test Method

10.7.4.1 Equipment Requirements

10.7.4.2 Procedure

10.7.5 Lighting Africa Recognized Test Method

10.7.5.1 Method 1 Electronics Efficiency Test for lighting products with mobile phone charging

10.7.5.1.1 Test Prerequisites

The autonomous runtime test must have been completed with accompanying logged current and voltage data at less than or equal to 5 minute intervals.

10.7.5.1.2 Test Outcomes

The output of this test is three efficiency values and a fraction α:

- Generator to battery efficiency (η_{G2B}) – the efficiency of the energy transfer from the power source (e.g. PV) to the lighting product's battery
- Generator to auxiliary efficiency (η_{G2A}) – the efficiency of the energy transfer from the power source (e.g. PV) to the auxiliary load (e.g. mobile phone)

- Battery to auxiliary efficiency (η_{B2A}) – the efficiency of the energy transfer from the lighting product's battery to the auxiliary load (e.g. mobile phone)

- Auxiliary charging fraction (α) – the fraction of daily auxiliary energy received directly from the generator (e.g. PV module). If the lighting product can only charge the auxiliary from the generator, α is 1. If the lighting product can only charge the auxiliary from its battery, α is 0. Otherwise, α is assumed to be 0.5, which means that auxiliary charging is split evenly during night and daytime.

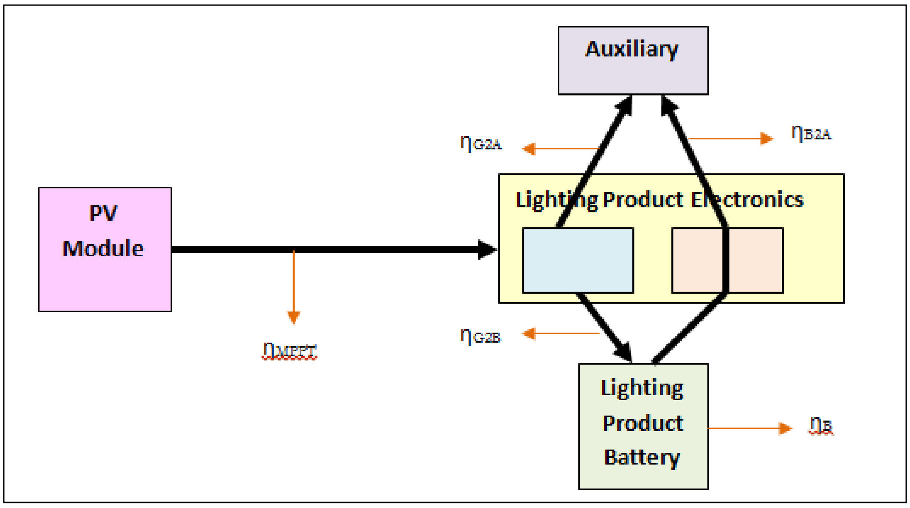

Figure B23: Visual of the efficiency values determined by this testing module.

10.7.5.1.3 Apparatus

This test is conducted in an area free of dust and maintained at a temperature within acceptable range according to the specifications of the battery analyzer.

10.7.5.1.4 Procedure

*Note: Procedure must be carried out in order within minutes of each other.

Equipment and sample preparation

- Discharge the lighting product battery such that it simulates when the battery is at half its full capacity.
    - To do this, first refer to the autonomous runtime current and voltage data logged.
    - Calculate the mAh's removed over the product's useful discharge (until reaching its L50).
    - Divide the number of mAh's removed by two to determine the mAh's removed after ½ its discharge ($mAh_{½}$).
    - Lookup the voltage value that the lighting product battery measured at the time it met ½ its discharge in the autonomous runtime test. This is the voltage at ½ its discharge ($V_{½}$).
    - Discharge the lighting product battery until it reaches its V½. This can be done with a voltage-set disconnect device or a battery analyzer.
- Discharge the mobile phone for testing to half way.
    - To do this, discharge the mobile phone to its V½ of 3.XV. (The standard Nokia XXX has a V½ value of 3.X V.) This can be done with a voltage-set disconnect device or a battery analyzer.

- Determine the solar charging current that corresponds to the $V_{½}$ from the lighting product's IV curve ($I_{½}$).

- Generator to battery efficiency (η_{G2B}) data collection
  - Charge the lighting product with a power supply for 2 minutes with $I_{½}$ current controlling. (Note: the auxiliary device is NOT plugged in at this time.)
  - After 2 minutes of charging the lighting product battery from the power supply, measure the following four values:
    - Current going into the lighting product battery
    - Voltage across the lighting product battery
    - Current coming out of the power supply at the lighting product's power input socket
    - Voltage across the lighting product's power input socket
  - Repeat taking these four measurements every 15 seconds over a minute. This provides a total of 4 readings for each of the four measurements.

- Generator to auxiliary efficiency (η_{G2A}) data collection
  - Plug in the mobile phone.

- After 2 minutes of auxiliary charging while still receiving charge from the power supply, measure the following seven values:
    - Current going into the lighting product battery
    - Current coming out of the lighting product battery
    - Voltage across the lighting product battery
    - Current coming out of the power supply at the lighting product's power input socket
    - Voltage across the lighting product's power input socket
    - Current going into the mobile phone
    - Voltage across the mobile phone's power input socket
- Repeat taking these four measurements every 15 seconds over a minute. This provides a total of 4 readings for each of the seven measurements.

- Battery to auxiliary efficiency (η_{B2A}) data collection
    - Turn off the power supply.
    - After 2 minutes of auxiliary charging from the lighting product battery, measure the following four values:
    - Current coming out of the lighting product battery

- Voltage across the lighting product battery

- Current going into the mobile phone's input socket

- Voltage across the mobile phone's power input socket

- Repeat taking these four measurements every 15 seconds over a minute. This provides a total of 4 readings for each of the four measurements.

10.7.5.1.5 Calculation

- Determining efficiency values

  - For each of the measurements taken for each of the efficiencies, determine the average over the four readings taken. There should be a total of 15 averaged values for all three efficiencies.

  - Using the average values from the generator to battery efficiency (η_{G2B}) data collection, determine the generator to battery efficiency (η_{G2B}) using the following equation:

$$\eta_{G2B} = \frac{\text{Energy into LP Battery}}{\text{Energy from Generator}} = \frac{I_B \times V_B}{I_{PS} \times V_{PS}}$$

Where,

η_{G2B} = Generator to battery efficiency
I_B = Averaged current into lighting product battery
V_B = Averaged voltage across lighting product battery
I_{PS} = Averaged current coming out of the power supply at the lighting product's power input socket
V_{PS} = Average voltage across the lighting product's power input socket

Using the average values from the battery to auxiliary efficiency (η_{B2A}) data collection, determine the battery to auxiliary efficiency (η_{B2A}) using the following equation:

$$\eta_{B2A} = \frac{\text{Energy into Auxiliary}}{\text{Energy from LP Battery}} = \frac{I_A \times V_A}{I_B \times V_B}$$

Where.

η_{B2A} = Battery to auxiliary efficiency
I_A = Averaged current going into auxiliary product's power input socket
V_A = Average voltage across the auxiliary product's power input socket
I_B = Averaged current into lighting product battery
V_B = Averaged voltage across lighting product battery

Using the average values from the generator to auxiliary efficiency (η_{G2A}) data collection, determine the generator to auxiliary efficiency (η_{G2A}) using the following equation:

$$\eta_{G2A} = \frac{\text{Energy into Auxiliary}}{\text{Energy from Generator to Auxiliary}} = \frac{(I_A \times V_A) - (I_{B\_out} \times V_B) \times \eta_{B2A}}{(I_{PS} \times V_{PS}) - \left(\frac{I_{B\_in} \times V_B}{\eta_{G2B}}\right)}$$

Where

η_{G2A} = Generator to auxiliary efficiency
I_A = Averaged current going into auxiliary product's power input socket
V_A = Average voltage across the auxiliary product's power input socket
I_{B_in} = Averaged current into lighting product battery
I_{B_out} = Averaged current coming out of lighting product battery
V_B = Averaged voltage across lighting product battery
I_{PS} = Averaged current coming out of the power supply at the lighting product's power input socket
V_{PS} = Average voltage across the lighting product's power input socket

- Determine the auxiliary charging fraction (α)
  - When performing test, if the auxiliary device could not be plugged in or no current was measured going into the auxiliary device, $\alpha = 0$.
  - When performing test, if the auxiliary device could not be plugged into the lighting product or no current was measured going into the auxiliary device, $\alpha = 1$.
  - If current could go into the auxiliary device assume $\alpha = 0.5$.

10.7.5.1.6 Reporting

- Report the following values.
  - Date(s) tested, and testing location
  - The product sample number(s), and all equipment specifications and serial numbers.

Table for example reporting

Value	Abbreviation	Significant Figures	Type
Generator to battery efficiency	η_{G2B}	3	Percentage
Generator to auxiliary efficiency	η_{G2A}	3	Percentage
Battery to auxiliary efficiency	η_{B2A}	3	Percentage
Auxiliary charging fraction	α	2	Number less than 1

11 APPENDIX C: ERROR ANALYSIS

In order to understand the error introduced in the Fraunhofer ISE model from the different input parameters, a first order error analysis was conducted on the model. This section details the equations and the input parameters used in the analysis.

The Fraunhofer ISE model is as shown in Equation 2:

$$\mathrm{SRT} = \mathrm{CF} \times \frac{\mathrm{EPV}}{\mathrm{EBatt}} \times \mathrm{ART} \qquad \text{Equation 2}$$

Where,

SRT is the solar runtime for the lighting product in hours

CF is the combined correction factor (PV_{mpp}, electronics and battery efficiency) for the lighting product

E_{PV} is the energy delivered to the battery from the PV module of the lighting product in watts

E_{Batt} is the total amount of energy that can be stored in the battery of the lighting product in watts

ART is the autonomous runtime of the lighting product in hours

Applying a first order propagation of error on the model we get Equation 4 below,

$$\frac{\sigma_{\mathrm{SRT}}{}^{2}}{\mathrm{barSRT}^{2}} = \frac{\sigma_{\mathrm{CF}}{}^{2}}{\mathrm{barCF}^{2}} + \frac{\sigma_{\mathrm{EPV}}{}^{2}}{\mathrm{barEPV}^{2}} + \frac{\sigma_{\mathrm{EBatt}}{}^{2}}{\mathrm{barEBatt}^{2}} + \frac{\sigma_{\mathrm{ART}}{}^{2}}{\mathrm{barART}^{2}}$$

Where,

σ_X is the standard deviation of the particular input

barX is the average value of the particular input

Applying the propagation error to the Fraunhofer ISE method results in a percent coefficient of variance (CV) for the SRT that varies from 14 to 19%. The highest value of percent CV was for Product 1 and Product 7, indicating higher variability in the input parameters for these lighting products. Similar analysis for the Revised Fraunhofer ISE method resulted in a percent CV ranging from 15 to 26%. The low percent CV was for Product 2, Product 4 and Product 6 and the high value of percent CV was for Product 5. The rest of the products ranged close to ten percent CV.

The difference in variability of the input parameters between the Fraunhofer ISE and Revised Fraunhofer ISE method is caused by the additional single point efficiency inputs into the calculation model. Overall, the additional inputs for the Fraunhofer ISE model added to the variability of the SRT estimate by 1 to 5 percent. For the Fraunhofer ISE method the fraction of variability introduced by the input parameters is generally equally divided between the correction factor, battery capacity and autonomous runtime (Table C7). For the Revised Fraunhofer model, the additional electronics and battery efficiency measurements are the main causes for the introduction of more variability (as compared to the Fraunhofer ISE model) in the system.

Table C6: Summary of the first order propagation of error for the Fraunhofer ISE and Revised Fraunhofer ISE method for estimating SRT for the lighting products used in this analysis. The last column for each model (%CV for SRT) is the percent coefficient of variance in SRT estimation.[20]

Fraunhofer ISE

Product ID	Correction Factor (CF)		Battery Capacity (Wh)		Autonomous Runtime (h)		PV panel Battery Energy (Wh)		**%CV for SRT**
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	
Product 1	52%	0.052	1125	112	2.80	0.28	1625	111.43	19%
Product 2	52%	0.052	1799	12	7.48	0.81	5645	21.21	15%
Product 3	62%	0.062	27564	2756	6.70	0.67	29925	35.36	17%
Product 4	52%	0.052	12528	1253	11.50	1.15	8950	141.42	17%
Product 5	52%	0.052	985	48	4.25	0.35	3067	12.58	14%
Product 6	62%	0.062	9309	931	8.80	0.88	14650	70.71	17%
Product 7	62%	0.062	15312	1531	9.85	1.20	7500	75.00	19%

Revised Fraunhofer ISE

Product ID	Electronics Efficiency		Battery Efficiency		PVmpp Efficiency		Battery Capacity (Wh)		Autonomous Runtime (h)		PV panel Battery Energy (Wh)		**%CV for SRT**
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	
Product 1	92%	0.009	63%	0.063	89%	0.028	1124.64	112.5	2.8	0.28	1625.0	111.43	19%
Product 2	25%	0.024	75%	0.027	95%	0.021	1798.8	11.9	7.5	0.81	5645.0	21.21	15%
Product 3	73%	0.102	84%	0.084	76%	0.021	27564	2756.4	6.7	0.67	29925.0	35.36	22%
Product 4	95%	0.021	80%	0.024	92%	0.010	12528	1252.8	11.5	1.15	8950.0	141.42	15%
Product 5	77%	0.09	80%	0.080	45%	0.080	984.6	48.4	4.3	0.35	3066.7	12.58	26%
Product 6	84%	0.016	95%	0.008	96%	0.035	9309.2	930.9	8.8	0.88	14650.0	70.71	15%
Product 7	72%	0.078	80%	0.080	80%	0.08	15312	1531	9.9	1.20	7500.0	0.00	24%

[20] In the case where more than one measurement was unavailable for the input parameters, a standard deviation of ten percent from the measured value was assumed.

Table C7: Summary of the fraction of variance resulting from each input parameters after applying the first order propagation of error for the Fraunhofer ISE and Revised Fraunhofer ISE method for estimating SRT.

Fraunhofer ISE				
Product ID	Correction Factor Fraction of %CV of SRT	Battery Capacity Fraction of %CV of SRT	Autonomous Runtime Fraction of %CV of SRT	PV panel Battery Energy Fraction of %CV of SRT
Product 1	0.29	0.29	0.29	0.14
Product 2	0.46	0.00	0.54	0.00
Product 3	0.33	0.33	0.33	0.00
Product 4	0.33	0.33	0.33	0.01
Product 5	0.52	0.12	0.36	0.00
Product 6	0.33	0.33	0.33	0.00
Product 7	0.29	0.29	0.43	0.00

Revised Fraunhofer ISE						
Product ID	Electronics Efficiency Fraction of %CV of SRT	Battery Efficiency Fraction of %CV of SRT	PVmpp Efficiency Fraction of %CV of SRT	Battery Capacity Fraction of %CV of SRT	Autonomous Runtime Fraction of %CV of SRT	PV panel Battery Energy Fraction of %CV of SRT
Product 1	0.00	0.28	0.03	0.28	0.28	0.13
Product 2	0.41	0.06	0.02	0.00	0.52	0.00
Product 3	0.39	0.20	0.02	0.20	0.20	0.00
Product 4	0.02	0.04	0.00	0.46	0.46	0.01
Product 5	0.21	0.15	0.49	0.04	0.11	0.00
Product 6	0.02	0.00	0.06	0.46	0.46	0.00
Product 7	0.21	0.18	0.18	0.18	0.26	0.00