Design and Construction of a Test Rig Prototype to Execute the Full-Battery Runtime Test for Pico-PV Systems

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Abstract— **In this paper I present the project of one test rig to measure the performance of Pico photovoltaic systems. The projected system consists of six photometer boxes, each equipped with an Arduino microcontroller and sensors for temperature, illuminance, voltage and current. One photometer box was built as prototype for evaluation purposes.**

For the measurement of voltage and current, a high side power monitor is used. The influence of the measurement shunt on the system to be measure is estimated with the help of two simplified circuits.

The microcontrollers are connected to an USB switch and communicate over a simple serial network. A program to analyse the sensor data is realised in Microsoft Excel.

The total cost for the test rig, including all components, is 543 €.

Keywords— Full-battery runtime test; Pico-PV lamps; Light measurement; Arduino microcontroller

I. INTRODUCTION

Pico-PV systems are small battery equipped solar lamps, which harvest energy during the day to light rooms during night hours.

The systems are primarily designed for unelectrified areas in developing countries with the goal to replace widespread kerosene lamps. However, low market entry barriers led to a plethora of low quality products. The mainly low-income customers had no means to distinguish between low quality and high quality products. As a consequence, the World Bank Group initiative 'Lighting Global' started in 2007 their 'Quality Assurance and Technical Service Program' in order to certify products that pass certain quality standards. One particular test is the full-battery runtime test that provides an indication of how long the system can be used with one battery.

The scope of this paper is to develop a prototype of a test-rig for this test.

II. DEVICES UNDER TEST

Pico-PV lamps vary in shape, size and technical specifications. All lamps have the basic construction in common and feature a small photovoltaic panel, an electro-chemical energy storage and a light source. Many lamps provide thereby the possibility to choose between two or more brightness. Current models exhibit in general some sort of battery management system. Moreover, most lamps are equipped with a LED driver or any other sort of LED protection mechanism.

The systems differ in battery chemistry and complexity of the electric circuit. The dominating battery chemistries are nowadays $LiFePO_4$ and NiMH.

III. THE FULL BATTERY RUNTIME TEST

The full-battery runtime test combines the battery efficiency, the circuit efficiency, and the lighting power consumption under operation. The primary test result is a time value that indicates the runtime at a specific light quality for a system with fully charged battery.

To determine the runtime, the light output of a completely charged lamp is measured every minute and logged together with voltage, current and a timestamp. The runtime is defined as the period between the first measurement and the point of time at which the light output has decreased to 70 % of the initial value. Moreover, the average relative light output is to determine as well as the current and voltage at this point.

TABLE I. OVERVIEW OVER TECHNICAL SPECIFICATIONS OF DIFFERENT LAMPS.

Type [V]	Voltage [V]	Luminous Flux [lm]	Current [mA]	Runtime [h]
Flash Light	4.8	350	115	5.5
Study Lamp	3.6	80	28	12
Lantern	6	102	51	9
Spot Light	3.3	162	310	1.1

IV. DESIGN CONSTRAINTS

The test rig should be especially simple to use and modify. The simplicity is important as the fluctuation in staff is high and the requirements on the test rig change regularly. As a result, the Fraunhofer decided to use Arduino microcontrollers for the test rig, which are especially simple to use. Moreover should the complete system cost than 600 €. The tolerance for voltage and current measurement is ± 1 %. The illuminance is measured in relative terms. Therefore a constant sensitivity and temperature stability is required.

V. SYSTEM OVERVIEW

The final system consists of 6 photometer cavities. One lamp is placed in each cavity, which is equipped with one Arduino microcontroller, one light sensor, one temperature sensor and one power monitor to measure battery voltage and current of the lamp. A microcontroller program was realised to gather the information from all sensors and forwards the data as comma separated values to the measurement PC once a minute via the serial interface. The data are finally analysed by a Microsoft Excel program.

A simplified overview of the system is displayed in Fig. 1. For the sake of clarity, the data recording on the measurement PC is not displayed. The cost of the final system was calculated to be 543 €.

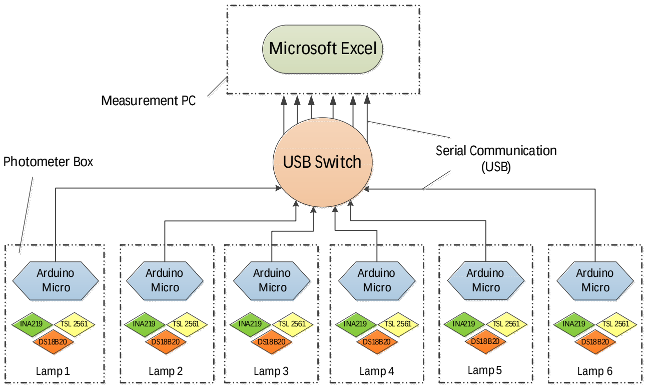

Figure 1. Overview over the final test rig design without data recording.

A. *Cavity Design and Sensor Placement*

Based on a literature review, three concepts for the measurement of light were analysed: an integrating sphere, a tube photometer and a box photometer.

As integrating spheres are too expansive and tube photometers are not suitable for lamps with wide spatial light distribution pattern, it was decided to use photometer boxes. Fig. 2 displays the prototype of the photometer box.

The dimensions of the measurement box are 43 cm x 29 cm x 26 cm. The interior walls of the box are painted with common wall paint. The sensor itself is mounted on a bent metal bracket. One part intrudes into the cavity interior and exhibits a 70 degree downward bent. The light sensor is installed on the bottom side of the bent part in ways that it faces a plain area of the cavity back side. The bent assures that the sensor does not see parts of the metal bracket or of its connecting wires.

The temperature sensor is installed close to the light sensor, as the measured temperature is used to correct the raw data of the light sensor by its temperature coefficient.

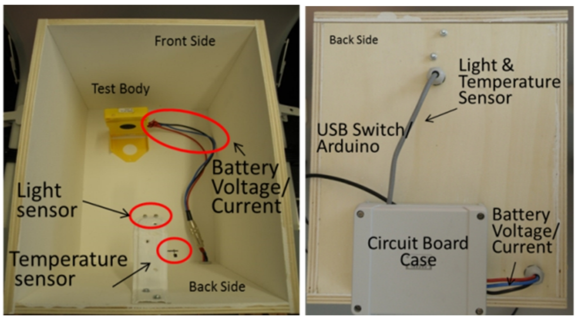

Figure 2. Top view into one of the photometer boxes (left). The cables to the lamp are normally hidden behind a white cover. View on the backside of the photometer box (right) with perforated board case.

The power monitor to measure current and voltage is installed on the perforated board, which is protected by a plastic casing. The temperature in the box is mainly dependent on the current to be measured. The temperature in the casing was measured to be 24.15 °C in thermal equilibrium at a current of 350 mA and an ambient temperature of 22.3° C. For looping-in of the measurement hunt, a permanent connection cable is installed. In order to measure current and voltage the connection cable is soldered into the current path of the lamp and the circuit is closed via the connector.

B. *Design of Microcontroller Network*

The data collected by the sensors have to be transmitted to a PC where the data is analysed.

Two different networks were designed and compared with each other.

The first concept is a master-slave concept that utilises the I^2C bus for communication. The slave devices collect sensor data of one measurement box and transmit the data to the master device via I^2C bus. The master device requests the data once a minute, composes the data and transmits it to a PC.

In the alternative network the microcontroller of each measurement box sends the data independently to the PC via an USB switch once per minute via the serial interface. As a consequence, many serial ports are needed to be monitored on the PC side.

The advantage of the first concept lays in the ease of handling. Only one serial port connection must be setup and all data is composed to one file. Conversely requires a change in test rig design, like the addition of another measurement box, a modification of code of the master and the slave devices. Moreover, the maximum capacitance of the I^2C bus is 400 pF. This limits the number of devices connected to the bus as well as the wire length between slaves and master. The advantage of the USB switch concept is its simplicity in design. After a change in test rig setup or extension no master device needs to be modified. The data are send from the microcontrollers directly to the PC via serial connection which reduces the length and complexity of the code significantly.

However, instead of setting up one serial connection, six connections need to be set up. In this application, the advantages of the USB switch concept outweigh the disadvantages.

C. *Used Microcontroller and Sensors*

The used microcontrollers are *Arduino Micros.* To measure current and voltage an INA219 high-side power monitor with a 12-bit resolution and a programmable gain amplifier (PGA) was used.

The PGA allows for an automatic adoption of the full-scale voltage for current sensing and ensures an appropriate step width even for small currents.

The used temperature sensor is a DS18B20 from *maxim integrated* and provides a 12-bit resolution. The communication between sensor and microcontroller is realised via the 1-Wire bus, which is a single line bus.

As light sensor, a Taos TSL2561 light to digital converter with 16-bit resolution and a measurement range from 1 lx – 40,000 lx is used. The sensitivity of the sensor has an approximate human eye response and is thereby suitable for photometric measurements.

All sensors have an integrated ADC and communicate either via the OneWire bus or the I^2C bus.

VI. CURRENT AND VOLTAGE MEASUREMENT

A. *Performance of Current and Voltage Measurement*

In order to evaluate the performance of the power monitor (INA219), a Fluke 5500A Calibrator was used as reference in combination with a standard cooling box and a Memmert UFE 400 oven as well as a Tinsley 5885 thermometer.

Random noise is quite high. At a real current of 50 mA the measurement result varies between 50.4 mA and 51.2 mA, resulting in a maximum difference of 0.9 mA or of 1.6 %. The zero drift for this particular senor was measured to be around 0.55 mA at 25 °C. To minimise random noise the arithmetic mean is calculated out of 100 consecutive measurements. From measurements at different temperature levels it was concluded that the power monitor is subject to temperature effects.

Therefore, a calibration table was created with 96 sampling points at a temperature of 25 °C. The correction value between two sampling points is interpolated. The same procedure is applied to the voltage values. Two measurement series at 14 °C and 35 °C for voltage and current were conducted and the raw data was corrected according to the calibration list. The biggest error occurs at the lowest end of the measurement range at (V, I) = (20 mA, 500 mV) and is in both cases between 0.2 % and 0.4 %.

To validate the results the relative error with a confidence level of 95 % based on 20 measurements was computed at 35 °C. For a voltage of 500 mV the error is 0.22 % - 0.26 % and at 20 mA 0.25 % and 0.35 %. In conclusion it can be said, that the accuracy of the INA219 is high enough for the desired application.

B. *Influence of the Measurement Shunt on the System*

By introducing a shunt the electrical system is changed. For lamps with constant current source and lamps with series resistor for current limitation, the general influence is estimated.

By four terminal sensing (Philips PM 6303 RCL) the total resistance of shunt and connection wires was measured to be 0.126 Ω.

Lamps with an LED driver regulate the current through the LED to a predefined value until the supply voltage drops below the minimum input requirements of the driver. The shunt causes a voltage drop V_{shunt} which can be determined according to Ohm's law. This voltage drop lowers the voltage at the input of the LED driver V_{in}. As a consequence, the minimum voltage input specification, is reached earlier. This minimum specification varies from lamp to lamp. Therefore no general conclusion can be drawn but the energy dissipation over the shunt can be calculated by

$$E_{shunt} = I^2 \cdot R_{shunt} \cdot t \, . \tag{1}$$

where E_{shunt} is the energy dissipated over the shunt, I is the current trough the shunt and R is the value of the resistance. The energy dissipated over the shunt is no longer available for the conversion to light. A rough estimation of the influence on the runtime is obtained by dividing the energy loss by the power consumption of the LED.

For lamps with series the INA219 introduces an additional shunt on the high side. As a consequence increases the voltage drop over the shunt, while the current through the circuit decreases. This leads to a new operational point which is determined by a lower current and lower LED voltage.

TABLE II. OVERVIEW OVER THE THEORETICAL RELATIVE ERROR FOR THE SOLAR RUNTIME MEASUREMENT CAUSED BY THE INA219.

Current [mA]	**Relative Error [%]**
75	-0.29
150	-0.58
200	-0.78
300	-1.16
350	-1.35

The total resistance of the INA219 with connecting wires and plugs for this examination is 0.151 Ω due to poor cabling. The influence of this additional resistance is thereby dependent on two factors.

The first factor is the ratio between the additional resistance and the original resistance. The higher ratio, the stronger decreases the gradient of the working line and the higher is the change in current. Lamps with a small series resistor will therefore be affected much more than those with big series resistors.

The second factor is the gradient of the LED characteristic. As the two influencing factors vary significantly from lamp to lamp, no overall valid conclusion can be drawn.

The real influence on lamp can be evaluated by measuring the current through the system (Fluke5500A calibrator) at a constant supply voltage (Agilent 34401A*)* both, with and without the measurement shunt (Table III).

TABLE III. EXAMPLE FOR THE INFLUENCE OF THE INA219 ON THE CURRENT FOR A LAMP WITH SERIES RESISTOR FOR CURRENT LIMITATION.

Undisturbed System			**Disturbed System**		
***Voltage* [V]**	***Current* [mA]**	***Resistance* [Ω]**	***Current* [mA]**	***Resistance* [Ω]**	***Error* [%]**
3.6716	60.000	13.052	59.421	13.202	-0.97
3.3410	40.000	13.050	39.600	13.207	-1.00
2.9955	20.000	13.070	19.795	13.221	-1.02

The difference in obtained resistance indicates that the measurement results are correct.

In conclusion, it must be said that the influence on the system is difficult to evaluate in a general way for both types of lamps. For lamps with a LED driver, it can be assumed that the influence on runtime and current is small if the current through the system is small. The runtime of lamps with series resistors is not influenced but only the current. A general conclusion is not possible as the factors vary from lamp to lamp.

It was seen that the influence on runtime and current of the examined model and lamp can be in the range of 1 % or even above. However, in consultation with the responsible test engineer at Fraunhofer Institute it was decided that those values are still in an acceptable range. A smaller influence could for example be achieved by using a smaller measurement shunt.

VII. MEASUREMENT BEHAVIOUR OF THE DS18B20 TEMPERATURE SENSOR

To evaluate the accuracy of the sensor, its measurement readings were compared to a Tinsley 5885 thermometer. In total, five measurements at 15 °C, 20 °C, 25 °C, 30°C and 35 °C were taken. For the analysis a standard cooling box and a Memmert UFE 400 oven were utilised. It can be seen that the absolute error is in the range of 0.2 °C to 0.3 °C. The accuracy of the sensor was improved by correcting all measurement readings by 0.25 °C.

VIII. TSL2561 LIGHT SENSOR

A. *Evaluation of Linearity*

The methods of how to correctly calibrate luminance meters is defined by the norm CIE69 [2] of the International Commission on Illumination (CIE).

According to the norm, a photometric standard is necessary. In praxis special equipment for an incremental variation of the illuminance is used. However, no standard luminance or special equipment is available at the ISE. Therefore, a calibrated photometer was used for comparison. As light source a Pico-PV lamp is used, connected to a programmable power supply (HAMEG HAMP 4040).

However, the lamp varies from an illuminance standard as the light output is neither completely diffuse nor is stable spatial distribution over time assured. To eliminate the spatial factor an integrating sphere is used. The TSL2561 was placed next to the permanently installed photometer. As light source three 24 V light bulbs with 100 W each were used. At 500 lx the relative measurement error was roughly 10.3 %.

During the execution of the test, the voltage was decreased in increments of 0.1 V. The installed photometer is a Luxmeter 110 with heated photometer head. The error of the photometer concerning linearity is given with 0.1 %. As only relative light measurements are conducted, the absolute value is not of interest, but merely the change of measurement error. The change in relative measurement error at a certain illuminance level $\Delta E_{\mathrm{rel},n}$ is defined as the relative measurement error at the initial illuminance level $E_{\mathrm{rel},i}$ subtracted by the relative measurement error at the considered illuminance level $E_{\mathrm{rel},n}$.

$$\Delta E_{rel,n} = E_{rel,i} - E_{rel,n} \qquad (2)$$

The change in relative measurement error is displayed in Fig. 3. Per definition is the change of the relative measurement error zero for the point of highest illuminance. For values near the lower end of the measurement range, the change in relative measurement error is the biggest. However, this doesn't necessarily show a poor behaviour of the sensor but could also be attributed to poor measurement readings, as it is impossible to log the measurement readings of the photometer and the TSL2561 at exactly the same time. Even in its thermal equilibrium the light output varies slightly. The results are shown in Figure 5.

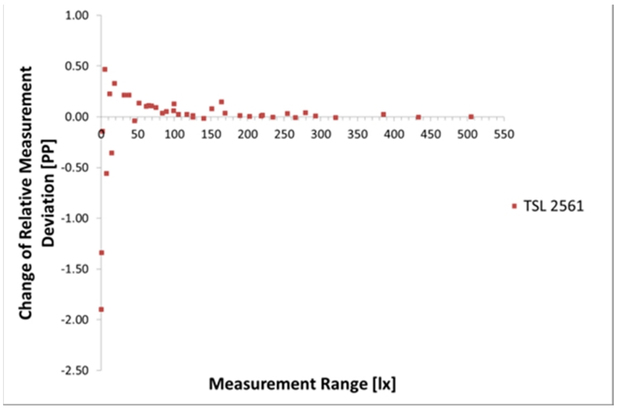

Figure 3. Change in relative measurement deviation at ambient temperature (24.4 °C). The change of relative measurement deviation is given in percentage point.

The measurement range of interest starts at 50 lx. Fig-3 shows that from 50 lx on, the relative measurement error are relatively constant. In conclusion it can be assumed that the TSL2561 is suitable for measurements at constant temperature.

B. *Estimation of the temperature coefficient*

The temperature coefficient f_6 is calculated according to:

$$f_6(25°C) = \frac{|Y(25°C) - Y(40°C)|}{Y(25°C)} \cdot \frac{1}{15°C} \cdot 100\% \qquad (3)$$

Where Y(T) represents the luxmeter reading at a specific temperature. A Pico-PV with two diffusor panels was used to replace the illuminance standard. A calibrated Luxmeter 110 was placed in front of the white surface with a TSL2561 attached right next to the sensitive area. The photodiode of the TSL2561 and the sensitive area of the photometer faced in the same direction, were installed at the same height and had an absolute distance to each other of 1.5 cm. The illuminance on the photometer and on the TSL2561 was found to be the same.

Five measurements were taken at 25 °C and 35° C during which the illuminance on the photometer was maintained to 600 lx. Due to temperature effects of the lamp, the supply voltage was slightly higher at 35° C. The results are shown in Table IV.

TABLE IV. VALUES OBTAINED FOR THE DETERMINATION OF THE TEMPERATURE COEFFICIENT. ALL VALUES ARE GIVEN IN LUX.

	25 Degree		**35 Degree**	
Nr.	***Photometer***	***TSL 2561***	***Photometer***	***TSL2561***
1	599.5	656.8	599.7	666.2
2	600	656.5	600.2	665.6
3	600.2	656.3	600.1	665.2
4	599.7	656.5	599.9	666.7
5	599.9	657.8	600.1	665.7

With the values from Table IV the temperature coefficient was calculated to be 0.138 % / K. The temperature coefficient of an unheated photometer with silicon photodiode (PCR Krochmann Luxmeter 110) is given with 0.1 %/K [3]. The coefficient for a comparable sensor like the one at hand (BH1750) is given with 0.067 %/K to 0.133 %/K. The estimated temperature coefficient is 38 % higher than the one of the luxmeter and at the upper boundary of BH1750. The computed value can therefore be assumed to be reasonable range. The maximum difference in temperature during one measurement (one day) was assumed to be 5 °C. If the computed value is wrong by 0.05 %/K the maximum error would be 0.25 % and still in an acceptable range.

IX. EVALUATION OF CAVITY DESIGN

The cavity is evaluated as a whole under real application conditions. To verify the quality of measurement, the light measurement is repeated in an integrating sphere with heated and calibrated photometer head. The key aspect under study is, if the kind of light emission influences the test result. Therefore, four different kinds of lamps were test: one study lamp, one lamp for room illumination, one flash light and one big spot light.

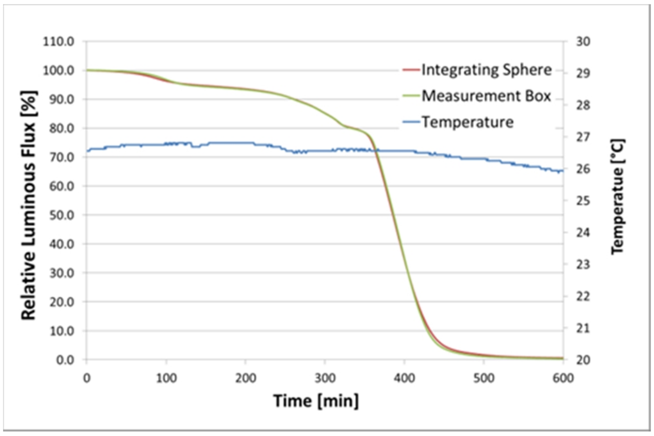

Figure 4. Comparison of light measurement results obtained in the self-built measurement box with a TSL2561 and in an integrating sphere. The light source is a lantern for room illumination that emits light in all directions.

The measurements were taken directly after each other. However, it is inevitable that the performance of the lamp differs slightly due to small differences in capacity, state of charge or temperature effects. However, the good match of results indicates that the type of spatial light distribution does not affect measurements in the box.

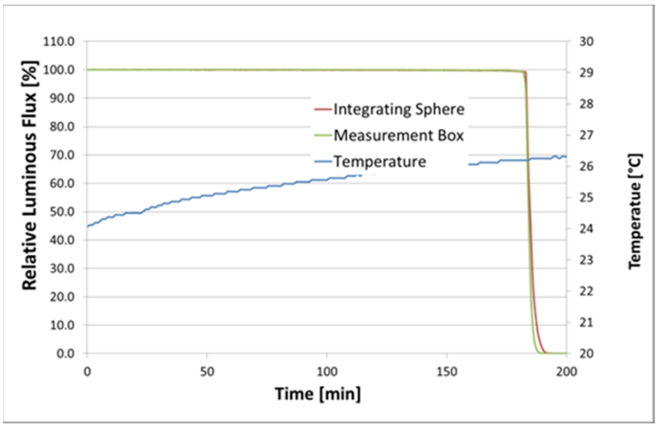

Figure 5. Comparison of light measurement results. The light source is a highly directional strong spot light lamp.

X. CONCLUSION

The simple but efficient design of the test rig provides the possibility to add additional measurement cavities without the need to make adjustments on the hardware or software of the original system. With the help of a programmable gain amplifier and the use of a calibration list the maximum relative error for currents measured at 35 °C was determined to be between 0.25 % and 0.35 % at a confidence level of 95 %. The computation of arithmetic mean values out of 100 measurement readings was found to be a sufficient method to eliminate random error caused by electrical noise. The influence of the measurement shunt was theoretically analysed with the help of two model circuits in dependency of the current. At the expected maximum current the relative error caused by the shunt is expected to be -0.97 % for systems with a series resistor and 1.35 % for system with constant current source. Both values are high but still in acceptable range. However for future systems the use of smaller shunt is advised. . By comparing the light sensor readings with the measurement readings of an integrating sphere, it could be shown that the sensor exhibits linearity in the required measurement range until 600 lx. Based on the procedure described in the standard CIE69, the temperature coefficient was estimated to be 0.138 %/K. A comparison with values of comparable sensors proofed the value to be realistic. The independence of the measurement result from the spatial distribution pattern could be shown by a systematic comparison with measurements taken with an integrating sphere. In conclusion it can be said that the performance proofed to be suitable for the desired application. Due to its simple and cost effective design it is can serve as example for the Lighting Global laboratory at Kenya.

XI. REFERENCES

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