Prototype Super-capacitor Photovoltaic Streetlight with xLogic SuperRelay Functionality

Rupert Gouws and Elizbe van Niekerk

Abstract: In this paper, the authors present and discuss the design of a prototype super-capacitor photovoltaic (PV) streetlight with xLogic SuperRelay (PLC) functionality. Deep-cycle batteries used in solar electrical systems, generally have low efficiencies, long charging times, are temperature sensitive and have a limited amount of charging and discharging cycles. This paper evaluated the effect of super-capacitors as an energy source for a PV streetlight in South Africa. An xLogic SuperRelay (PLC) is used to control the charging and discharging profiles of the super-capacitors and deep-cycle batteries. The following three design topologies are evaluated and presented: 1) deep-cycle batteries as an energy source, 2) super-capacitors as an energy source, 3) combination deep-cycle batteries and super-capacitors as an energy source. The experimental results obtained show that the deep-cycle batteries provide a constant supply to the load, while the super-capacitors charge and discharge with a linear curve. The results show that it is too expensive to replace deep-cycle batteries with super-capacitors, but a combination provides the most energy efficient solution.

Keywords: Energy management, photovoltaic arrays, programmable logic controller, super-capacitors.

I. INTRODUCTION

Currently there is a big drive towards renewable energy and electricity has become a scarce resource in the World. Photovoltaic (PV) street lighting was initially used in areas were electricity was not available. In South Africa, street lighting accounts for about 24% of the total energy consumed by South African municipalities and contribute for about 28% of the carbon emitted by municipalities in the delivery of services [1]. Furthermore most PV systems use deep-cycle batteries for energy storage, which have low efficiencies of about 70%, whereas super-capacitors (also known as ultra-capacitors) have high efficiencies ranging between 95 – 98%. PV systems require batteries with a life cycle of about 3 000 cycles [2]. Standard batteries can only produce hundreds and sometimes thousands of cycles and have a life expectancy of about 2 – 3 years [3]. Super-capacitors on the other hand can produce about 1 000 000 cycles and have a life expectancy of about 7 – 10 years [3]. It was therefore decided to design a prototype super-capacitor PV streetlight with xLogic SuperRelay (PLC) functionality. The PLC functionality was added to increase the efficiency of the total developed system.

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More detail on the functioning of the PLC is presented in the materials and method section. For this project three different design topologies are evaluated and presented: 1) deep-cycle batteries as an energy source, 2) super-capacitors as an energy source and 3) combination deep-cycle batteries and super-capacitors is an energy source. The following provides an overview of the main components of a PV streetlight:

- Solar panels: Solar panels produce and provide electricity by converting the energy coming from the sun into electricity. There are different solar panels available and each designed for a specific purpose. Suitable solar panels must be chosen for specific tasks and factors like bad weather conditions must be taken into consideration.
- Control unit: It is the circuitry that controls the solar power system. The purpose of a solar controller is to prevent batteries from overcharging and also to prevent back flow of current from the batteries to the solar panels. Most present controllers also have the advanced of preventing the battery from fully discharging. A solar charge controller is found between the solar panels and the batteries and must fed the batteries with the required voltage and amperage coming from the solar panels. A programmable logic controller (PLC) can also be used for specific controlling purposes. Ko and Chung [4] provides a novel control strategy of a PV tracking system which considers the shadow influence. Their proposed method calculates the distance between PV arrays using azimuth of solar, and calculates the shadow length of the PV array using altitude of solar [4].
- Energy source: Batteries are normally used as energy sources for PV streetlights. The solar panel charges the battery and at night the battery will discharge to provide energy to the light. In bad weather the batteries must be able to provide energy to the streetlight. A battery's life expectancy can be expanded by placing a super-capacitor bank in parallel with the battery or the battery can just be replaced by a super-capacitor bank. Examples where batteries and super-capacitors are placed in parallel is in Hybrid-electrical Vehicles (HEV) or Electrical Vehicles (EV) [5]. Super-capacitors are also used as the primary energy source in toys, emergency devices, cordless tools, etc. Min, Kim and Hur [6] provides a novel approach for optimized installation and operations of battery energy storage system (BESS) and electric double layer capacitor (EDLC) modules for the renewable energy based intermittent generation. Their proposed method adopts the linear programming to calculate the optimized capacity as well as

the quadratic programming to transmit the optimal operational signals to BESS and EDLC modules [6].

• Load: Different lamps are available for the usage of solar streetlights' loads, such as LEDs, compact fluorescent lamps (CFLs), high intensity discharge lamps, low pressure sodium lamps or metal halide lamps.

II. MATERIALS AND METHOD

This section provides the materials and method used to design the super-capacitor PV streetlight with PLC functionality.

A. Materials

Fig. 1 provides the conceptual design of the super-capacitor PV streetlight with PLC functionality. The following provides an explanation of each of the building blocks of the conceptual design:

• Solar panels: Mono crystalline solar panels are a bit more efficient than poly crystalline solar panels although poly crystalline solar panels are lower in cost are than mono crystalline solar panels.

• Control unit: The control unit will control the solar power system. The most popular control units available are Pulse-Width-Modulated (PWM) and Maximum Power Point Tracking (MPPT) controllers. For this project an xLogic SuperRelay (PLC) was selected for controlling purposes.

• Energy source: Sealed lead acid batteries and gel batteries are currently very popular to use. It is recommended that deep-cycle batteries are used for solar electric systems. Super-capacitors are available in different sizes and have different manufactures. An integrate kit was used to integrate the super-capacitors with each another. Comparison between super-capacitors and batteries can be seen in table 1 [7].

• Lamps: Different lamps are available for the usage of solar streetlights. For this prototype project it was decided to use a 6 W LED.

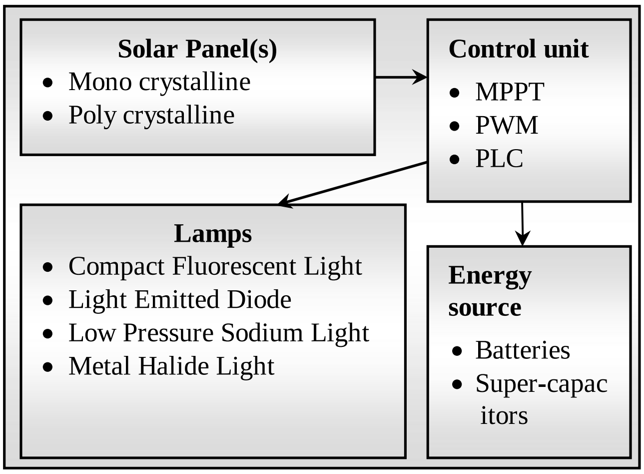

Fig. 1. Conceptual design of the PV streetlight.

B. Method

Fig. 2 provides an overview of the design methodology. The first step in the design of the PV streetlight is to specify the lamp load. Then from the lamp load the size of the batteries and super-capacitor can be calculated. Lastly from the size of the batteries, the size of the PV modules can be calculated.

Table 1. Super-capacitors and batteries comparison.

Super-capacitors	**Batteries**
Efficiency: 95%-98%	Efficiency: 70%
Low energy	High energy
High power	Low power
Fast charging time	Long charging time
Fast discharge time	Long discharge time
Operating temp: -40°C to 65°C	Operating temp: 20°C to 60°C
"Unlimited" cycle life, about 1 000 000 cycles	Hundreds/thousands cycles
Low equivalent series resistance	Higher internal resistance
Fully discharge: 100%	Deep-cycle batteries discharge: 50% to 80%

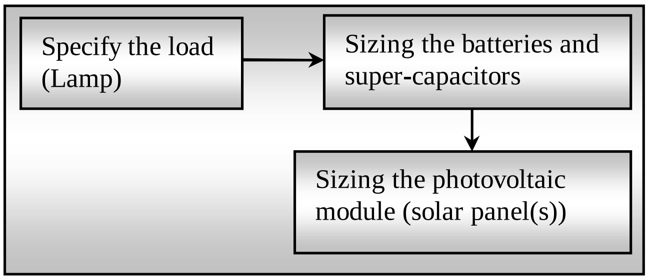

Fig. 2. Design methodology of the PV streetlight.

The following provides more detail and calculations on the design methodology:

The load demand was chosen at 6 W, therefore the total load demand for a 10 hours per day streetlight is 60 Wh/day. The capacity of the battery (A/h) can be calculated by means of equation (1):

$$\frac{(x \text{ number}) \text{ Wh/day x 3 (cloudy and rainy days)}}{\text{0.8 (20\% deep discharging) x 12 (nominal battery voltage)}} \quad (1)$$

A 7 A/h deep-cycle battery was selected and will let the load burn for about 5 hours. The load demand of 6 W for 5 hours will therefore be 30 Wh/day.

Sizing the super-capacitors: Super-capacitors usually used for solar systems are in the range of 650 F – 3000 F. For this project it can decided to use six 3000 F super-capacitors. Super-capacitors only provide a rated voltage of 2.7 V, since it is required to place them in series to obtain a 12 V PV system. The number of cells to put in series and the total capacitance to be placed in series are calculated with by means of equations (2) and (3), respectively.

$$\#\ \text{series cells} = \frac{V_{\max}}{V_r} \quad (2)$$

Where V_{max} is the maximum working voltage and V_r is the super-capacitor's rated voltage.

$$C_{total(i)} = \frac{C_{cell}}{\#\ \text{series}} \quad (3)$$

Where $C_{total(i)}$ is the total series capacitance and C_{cell} the capacitance of a cell.

The amount of time that the super-capacitors can supply energy to the load is calculated by means of equation (5). Equation (4) provides another equation to calculate the total capacitance.

$$C_{total(i)} = (i_{avg})(\frac{dt_i}{dV}) + (i_{avg})(R) = (i_{avg})(\frac{dt_i}{dV}) + (i_{avg})(\frac{\tau_i}{C}) \quad (4)$$

And

$$dt = \frac{C_{total_i}}{i_{avg}} \text{ x dV} \quad (5)$$

Where i_{avg} is the average current, d_t the time in seconds that the super-capacitor will operate and d_V is the voltage drop.

Sizing the solar panel: There are many aspects to consider when sizing a solar panel, such as: hours of sun per day, load demand, solar radiation in the area and the mounting angle of the solar panel for optimal solar radiation.

Firstly it is important to obtain the amount of power per day that will be demanded from the solar panel by the system. The calculations are as follows: load demand (W/h) x 1.3 (energy losses caused by the system) = (x_2 number) Wh/day (must be provided by the solar panels). The lowest solar radiation in Potchefstroom (South Africa) is 3.64 kWh/m2/day, which were used for the calculations [1].

The watt-peak rating of the solar panels required (kWh/day) is provided by equation (6).

$$\frac{(x_2 \text{ number) kWh/day}}{\text{3.276 (solar panel generation factor)}} \quad (6)$$

The solar panel generation factor is the collection efficiency of the solar panels multiplied by the lowest monthly solar radiation in a year. To obtain the amount of solar panels required, are calculated by the following equation: Wh/day (watt-peak rating) / (solar panel size of choice) = photovoltaic modules. Therefore only one 30 W solar panel is required and will be used for this prototype system.

Sizing the solar regulator/controller: The charge current of the solar regulator is calculated by means of equation (7).

$$C_c = \frac{\text{30 W (power output of solar panel)}}{\text{12 V (nominal battery voltage)}} = 2.5 \text{ A} \quad (7)$$

The maximum charge current of the solar regulator is calculated by means of equation (8).

$$C_{c\max} = C_c \text{ x 1.2 (safety factor)} = 3 \text{ A} \quad (8)$$

A solar regulator with a maximum charge current of 3 A were therefore selected. It was decided to use the Steca Solum 6.6 F solar regulator as it is easy to install.

Programmable Logic Controller (PLC): The xLogic SuperRelay (PLC) was used and was programmed with xLogic software. The software includes logic building blocks to program the device. The xLogic SuperRelay was programmed with the basic AND, OR and NOT function blocks. The PLC is programmed to charge the super-capacitors to 12 V and discharge to 6 V, since the lights turn off at 6 V. Super-capacitors can further be discharged to 0 V, without damaging them. The PLC is programmed to charge the battery to 13 V and discharge to 11 V. The xLogic SuperRelay is programmed to first discharge the super-capacitor bank and then discharge the battery.

III. EXPERIMENTAL RESULTS

This section provides the experimental results obtained from the super-capacitor PV streetlight with PLC functionality. The experimental results were recorded during a period of no clouds and no rain and the solar panel was placed to obtain the maximum solar radiation. The complete system was simulated in PVsyst®, which showed that the ideal solar panel mounting angle is 28° for the Potchefstroom (South Africa) area.

A. Battery as an energy source

The system containing a battery as an energy source gave a constant charging and discharging voltage profile as expected.

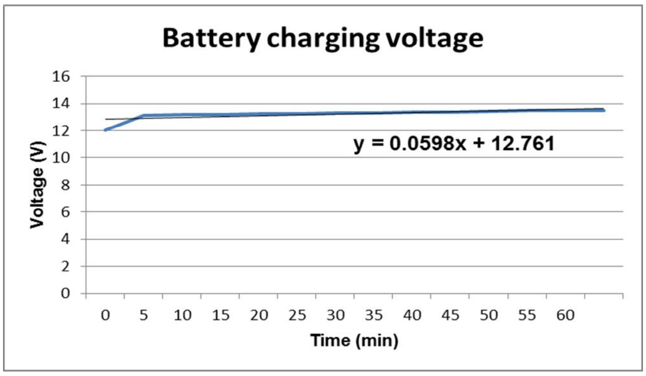

Fig. 3. Battery charging voltage profile.

The battery's discharging profile is presented in fig. 4. The battery provided an overall constant supply voltage with a slightly decrease in the battery's voltage over time until the battery supply is being cut off by the solar regulator to protect the battery from deep discharging. The Steca Solum 6.6 F solar regulator is designed to cut a 12 V battery's voltage off between 11.2 V – 11.6 V during discharging. Thus the measurements show that the solar regulator indicated a weak battery voltage at about 11.8 V and the light stop shining. The battery was able to provide the light with energy for about 5.5 hours (330 minutes) as indicated in fig. 4.

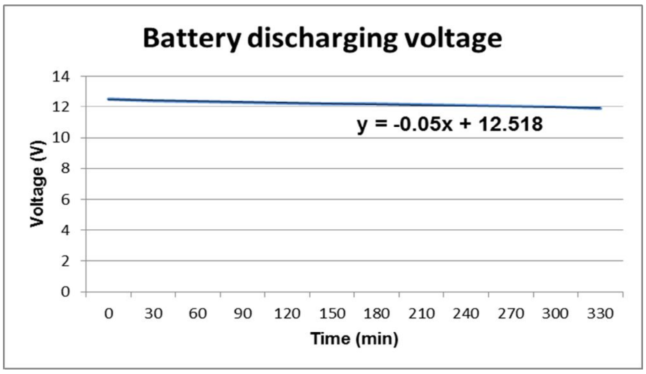

Fig. 4. Battery discharging voltage profile.

The battery's discharging load current was measured between 0.45 A – 0.47 A for the full discharging period. Therefore it indicates that a battery provides a constant energy supply and let the light shine with a slight change in brightness throughout the discharging period. The discharge profile provides a linear curve and has a gradient of -0.05.

B. Super-capacitor as an energy source

Figs 5 and 6 provide the charging and discharging voltage profiles of the super-capacitor bank. From fig. 5 it can be seen that the super-capacitor bank charge in only 50 minutes, which is one of super-capacitor's greatest advantages. The charging time for super-capacitors is much faster than for batteries.

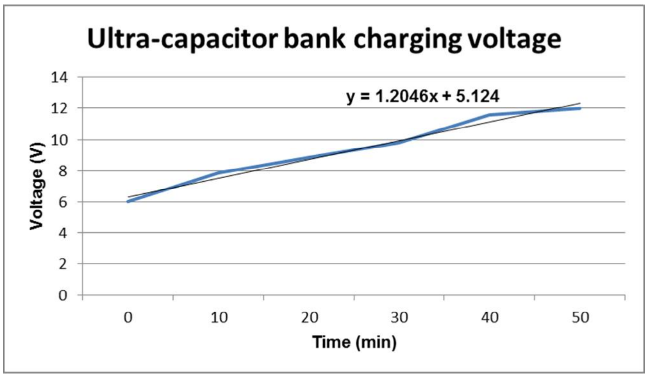

Fig. 5. Super-capacitor charging voltage profile.

When comparing the two figures it can be seen that the charge and discharge profiles result into two linear profiles. As it is a characteristic of super-capacitors that the charge and discharge profiles are linear, it can be concluded that the super-capacitor bank operates normally in this system. From fig. 6 it can be seen that the super-capacitor bank discharges until about 4 V before the lights switches off, but as from 6 V – 4 V the lights intensity are very weak. Therefore for efficient lighting the super-capacitors discharges for about 75 minutes when it reaches 6 V.

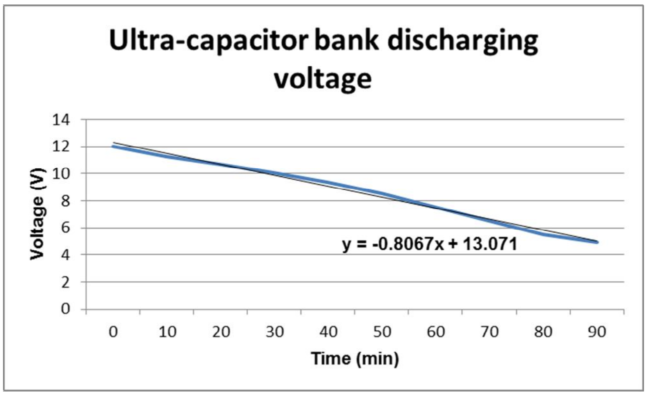

Fig. 6. Super-capacitor discharging voltage profile.

Fig. 7 provides the load current profile at the beginning of the discharging period at 0.5 A as expected with a 12 V energy source and a load demand of 6 W. As the voltage of the super-capacitor bank drops, the current increases until there is not enough energy left to provide the load. The current also drops, which states the fact that the light intensity from 6 V – 4 V are very weak. The lights will be efficient until the super-capacitor bank reaches 6 V. The highest current demanded by the 6 W load is 1 A that was reached at 6 V when comparing fig. 6 and fig. 7.

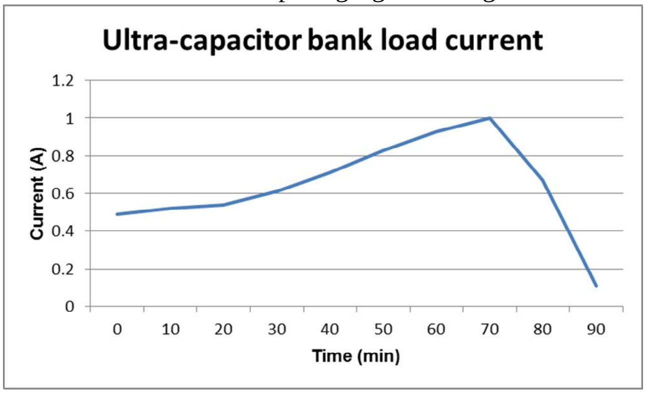

Fig. 7. Super-capacitor load current profile.

C. Battery and super-capacitors as an energy source

Fig. 8 provides a photo of the prototype super-capacitor PV streetlight with xLogic SuperRelay (PLC) functionality and deep-cycle battery. In this figure the super-capacitors, photovoltaic panel, deep-cycle battery, PLC and light can be seen. A PLC is used to control the system as described in the materials and method section.

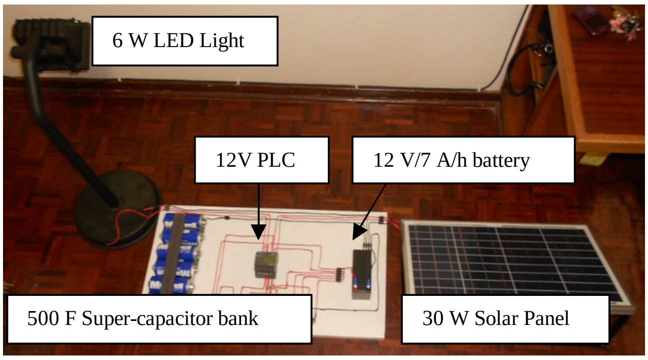

Fig. 8. Experimental test setup system.

Fig. 9 provides the charging and discharging voltage profiles of the combination (battery and super-capacitor) system. From this figure it can be seen that the battery and the super-capacitor bank charges at the same time until the super-capacitor bank is fully charge. After about 50 minutes only the battery charges for another 90 minutes until fully charged while the super-capacitor bank is fully charge at 12 V within 50 minutes. The control is performed by the xLogic SuperRelay (PLC).

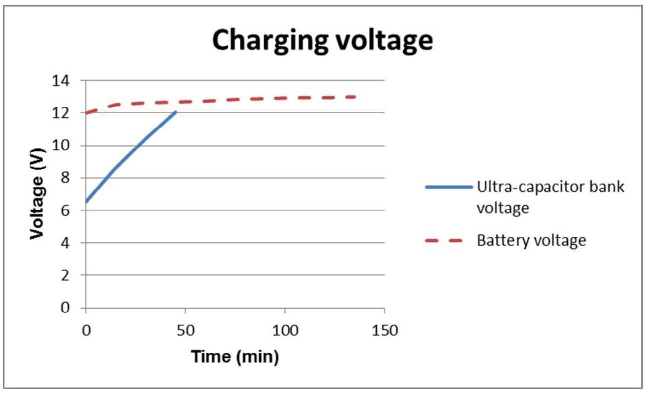

Fig. 9. Battery and super-capacitor charging profiles.

Fig. 10 provides the battery and super-capacitor discharging voltage profiles. The super-capacitor bank discharge just above 6 V in about 80 minutes and then the PLC switches from the super-capacitor bank as the energy source to the battery as the energy source. In the switching time the light goes off for a split second until relay 4 is opened and relay 3 is closed of the PLC for discharging the battery until just above 11 V.

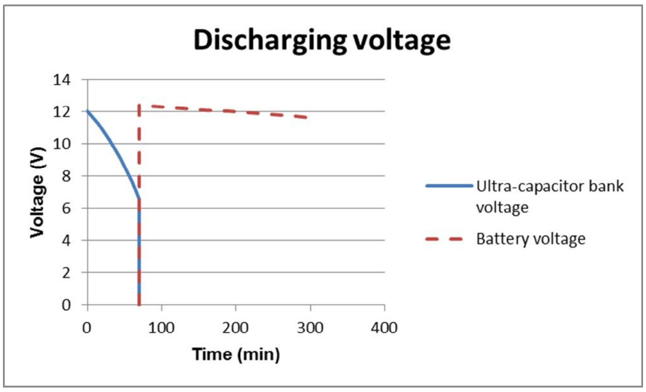

Fig. 10. Battery and super-capacitor discharging.

Fig. 11 provides the current drawn from the energy source by the load. It can be seen that if the super-capacitor bank voltage drops the current increases and the battery provides a constant load current for the load. This complete system provides sufficient energy to let the light shine for about 5 hours, this is because the super-capacitor bank switches off at 6 V in about 80 minutes and the battery are only charge to 13 V and not higher as discussed earlier.

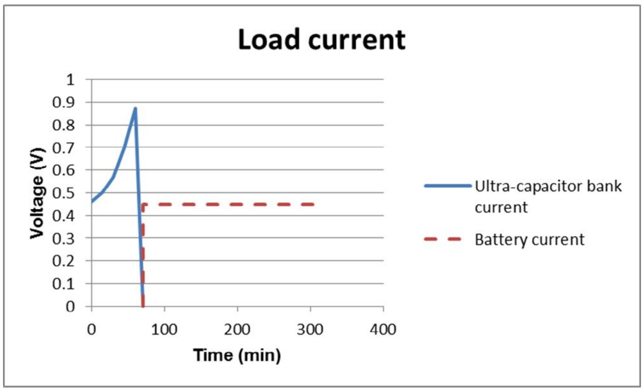

Fig. 11. Battery and super-capacitor load current.

D. Economical evaluation

The greatest advantage of super-capacitors is there long life time of about 1 000 000 cycles compared to only about thousands of cycles for batteries. Super-capacitors also have a life expectancy of about 10 years at rated voltage (2.7 V) and at a room temperature of about 25°C. Normally batteries are being discharge to an 80% charge and therefore PV systems required about 3 000 life cycles of batteries [2]. The battery that was used for this project has a life expectancy of about 5 years.

If considering the life cycles of each energy source discussed above, one super-capacitor bank will be used when batteries would have been used and replaced for several times. It can be calculated that super-capacitors have (1 000 000 / 3 000) 333.33 life times more than required PV batteries.

If only super-capacitors are being used as an energy source for this project, it would be very expensive. The super-capacitor bank only provides sufficient energy to let the light shine for about 90 minutes. From fig. 12 it can be seen what a super-capacitor bank will cost to let the light shine for only 12 hours (720 min) without considering bad weather conditions when back-up power is required for 3 - 5 days.

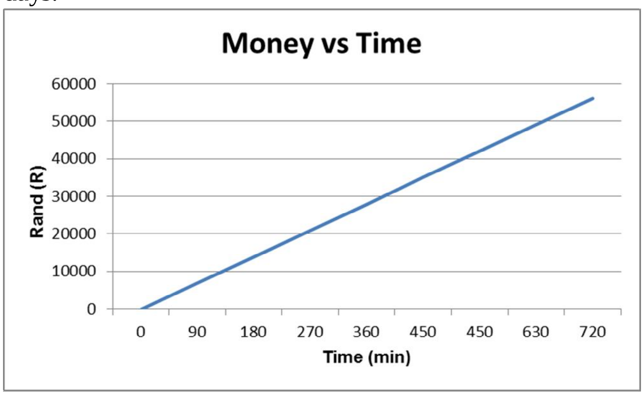

Fig. 12. Super-capacitor bank cost analysis.

IV. CONCLUSION

For this project a prototype photovoltaic streetlight with xLogic SuperRelay (PLC) functionality was designed and built. The aim was to evaluate three systems with three different energy sources (battery and/or super-capacitors). The systems included a 30 W PV module, 12 V / 7 A/h deep-cycle battery, 500 F super-capacitor bank, a solar regulator, an xLogic SuperRelay PLC and a 6 W LED load.

The first system was the system with the battery as an energy source. As expected it provided a constant energy supply to the load for a period of about 5.5 hours, as shown in fig. 4. The second system was the system with the 6 super-capacitors in series as an energy source. A total of 6 super-capacitors were used in series to provide the required 12 V. The results obtained shows that the super-capacitors charged to 12 V within 50 minutes and for efficient lighting it discharged in about 70 - 80 minutes.

It is shown that the cost of replacing batteries with super-capacitors is very high. Although super-capacitors have a very long life time of about 1 000 000 life cycles the initial cost to install such a system will be unrealistic when considering it for a standard PV streetlight. When a standard PV streetlight must be implemented it is very important to include backup energy for rainy and cloudy days and thus such a system's would cost even more.

When considering the third system (battery and super-capacitor bank combination), it can be seen that the life expectancy of the battery can be extended by including super-capacitors. Super-capacitors have about 333.33 life time more than batteries and if used together with batteries can provide a PV streetlight's load for the first half or quarter of a night. If the super-capacitor discharging time represented a half or quarter night time it would just let the battery discharge to about 96% or 92% charge respectively (less than 10% discharge), but the battery can be used when bad weather conditions is present and a long discharging time is required.

Lee, et al. [8] provides a novel algorithm that determines the power and storage capacity of selected energy storage devices in order to improve upon railroad system efficiency. According to Lee, at el. [8] their algorithm can determine the optimized power and storage capacity of the storage devices for the efficiency and the stabilization of the feeder voltage.

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