

Technical Notes

Issue 4 April 2011

Lighting Efficiency and Product Design Optimization

This Technical Note discusses lighting product design from an energy and efficiency perspective. It is intended to help *manufacturers* design efficient, high performance products and avoid the false choice between good performance and low product cost.

The Information contained in this article builds on previous Technical Notes. See also: <http://www.lightingafrica.org/resources/briefing-notes.html>

Introduction

Efficiency is a critically important subject for off grid lighting products. Light output, run times, and solar charging rates are directly dependant on the efficiency of the energy collection and energy use of these systems. High efficiency will enable more light output, for longer periods of time, with lower energy input. Energy efficient design can benefit the manufacturer by reducing product costs, and also benefit the end user by enabling higher quality products.

This Technical Note begins with definitions and explanations of lighting efficiency terminology, and then goes on to describe the specific efficiencies present in a typical lighting product. The final part of the document provides examples showing how efficiency affects the performance and energy requirements of a battery powered LED lamp that generates 100 lumens of light.

Light Output and Efficacy

The amount of visible light produced by a light source is determined by the power input (in watts, W) and the source efficacy (in lumens per watt, lm/W). **Efficacy** is defined as the ratio of light output to power input, and represents the ability of a light source or lighting system to efficiently convert electrical energy to visible light. Efficacy performance can relate to a single LED, a CFL lamp, or an entire lighting system or light fixture including optics, electronics, and fixture housings. When using efficacy in lighting calculations, it is important to specify which system components are included in the measurements.

The general equation for light output can be written as:

$$\text{Light Output (lm)} = \text{Efficacy} \times \text{watts}$$

$$(lm/W) \quad (W)$$

Equation 1

Increasing either the power input or the efficacy will increase the amount of light output.

LED Efficacy

For LEDs, there is a limit to amount of power that the individual device can handle. Too much power can overheat the LED chip, damage the device and lead to rapid lumen depreciation (where the light output levels decrease quickly over days, weeks, or a few months).

	Lumen Output	Junction Temp	Efficacy	Lifetime
Increased LED drive current	higher ↑	higher ↑	lower ↓	lower ↓
Decreased LED drive current	lower ↓	lower ↓	higher ↑	higher ↑
Improved LED heatsinking	higher ↑	lower ↓	higher ↑	higher ↑

Table 1: LED Performance Variables

Increasing the power to an LED increases the light output but **DECREASES** the efficacy because the LED chip will run at a higher temperature (Table 1). This means that a designer cannot simply double the amount of power in order to double the light output. Doubling the efficacy (by using a more efficient LED source) **WILL** double the light output, so the selection of a higher quality LED should always be considered.

For example, consider an LED lighting product that uses an array of 6 LEDs to produce 12 lumens of light. Each LED outputs 2 lumens and has a source efficacy of 28 lm/W (the rated power of each LED is 0.072 W). The total power of the LED array would be $0.072 \times 6 = 0.432 \text{ W}$. If more efficient LEDs (with source efficacy = 56 lm/W) were used, the same amount of power would give $0.432 \text{ W} \times 56 \text{ lm/W} = 24 \text{ lumens}$, or 4 lumens per LED. If 3 LEDs were used instead of 6, the lumen output would be back to 12 lumens but the total LED array power would fall to $0.072 \times 3 = 0.216 \text{ watts}$.

Optical Efficiency

Lighting products often use some type of cover to protect the light source (LEDs or CFLs) from dirt, water, and physical damage. These covers can be lenses, diffusers, or simply clear plastic, and often will be combined with reflectors or reflective surfaces to shape and control the light distribution.

Any material (lens or reflector) will absorb some light. In the case of a lens, diffuser, or clear cover, these transmissive materials allow light to pass through and absorb, reflect, or scatter some percentage as well. Clear acrylic and polycarbonate absorb at least 8% of the light and transmit less than 92%, although the transmission can be lower depending on the specific material, the angle of incidence of the light, the material thickness, and the surface quality. **It is important to understand that any transmissive material will absorb, scatter, or lose some amount of light (see Figure 1 below).**

The same is true of reflective surfaces inside the light fixture. Mirrored (specular) surfaces reflect much of the light and can be > 95% efficient. Semi-specular and diffuse reflectors, such as white plastic, can reflect anywhere from 50 – 90% of the light. Again, some light is always lost when reflecting off of these surfaces.

$$\text{Light Output (lm)} = \text{LED Output (lm)} \times \text{optical efficiency}$$

Equation 2

In the example lighting product from the last section there are 3 LED's that produce 12 lumens. When these LEDs are placed into a housing, and a lens and reflectors are used to protect and shape the light output, some of the light is lost. In this case, suppose that the combination of lens and reflector loses 30% of the light. This means that the optics have an efficiency of 70%, and the lighting product (with the optics installed) will emit $12 \text{ lm} \times 70\% = 8.4 \text{ lumens}$.

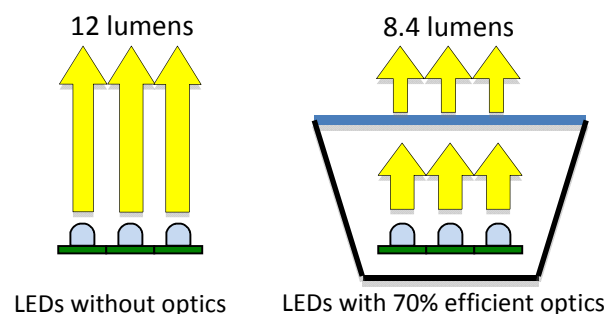


Figure 1: Optical losses from reflectors and lenses

To determine the efficiency of the optics, it is necessary to test the lumen output of the LED array with and without the optics installed as illustrated in Fig 1. This can be difficult with some optical geometries where the LEDs are integrated with a heat sink that also has an optical function, and also where the optics can affect the heat dissipation of the LED array. Knowing the optical efficiency, while not absolutely mandatory, is a valuable tool for the manufacturer or designer interested in optimizing their design and getting the most out of the LED or LED array (Figure 2).

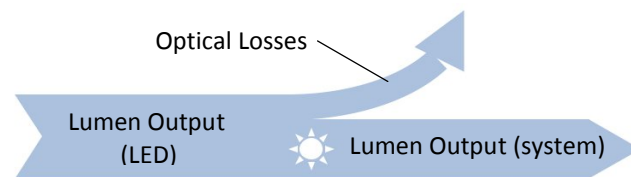


Figure 2: Optical losses depicted by an energy flow diagram

Electrical Efficiency

No electronic device is 100% efficient. There will always be electrical energy losses (power losses) associated with running LEDs or CFLs in a lighting product. These energy losses occur in the wires, resistors, components, etc. that make up the electronic driver or ballast. (Fig 3)

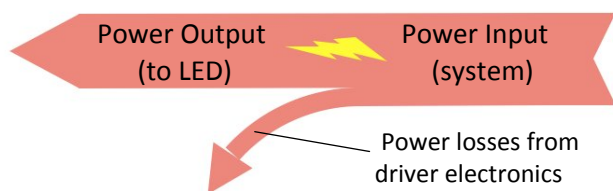


Figure 3: Power loss diagram of 75% efficient system

The electronic efficiency of a driver or ballast is the ratio of the power output (from the driver to the light source) to the system power input (from the battery to the driver). The power input will always be higher than the power output.

Power can be expressed as current x voltage:

$$\begin{array}{ccccc} P \text{ (power)} & = & I \text{ (current)} & \times & V \text{ (volts)} \\ \text{watts} & & \text{amps} & & \text{volts} \end{array}$$

Equation 3

Electronic (driver) efficiency will then be:

$$\text{Driver efficiency} = \frac{P_{LED}}{P_{system}} = \frac{I_{LED} \times V_{LED}}{I_{system} \times V_{system}}$$

Equation 4

P_{LED} = power output from driver to light source

P_{system} = power input to driver or ballast

I_{LED}, V_{LED} = current and voltage output from driver to light

I_{system}, V_{system} = current / voltage input from battery to driver

The efficiency of electronic drivers and ballasts can vary widely. For LED systems, efficiency can be measured with a multimeter that measures the electrical current and voltage first between the power source (usually a battery) and the electronic driver circuit, then between the driver circuit and the light source (Fig 4).

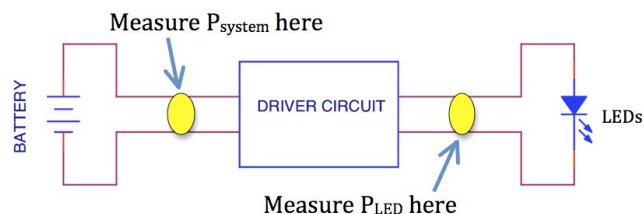


Figure 4: Simplified schematic with measurement points

The electronic efficiency affects the power consumption and efficacy (lumens/watt) of the system. For battery systems this is especially important, as a higher electronic efficiency will mean longer run times. (Note: the electronic efficiency discussed here deals only with energy losses in the driver control circuitry. For battery powered systems, there is also energy loss from the internal resistance of the battery itself.)

System Efficiency and Lumen Output

All of the component efficiencies of a lighting product can be combined to determine the total system efficiency and lumen output of the device. This information is used to determine system power levels, autonomous run time, and the required battery capacity and solar panel size to meet certain performance goals (Figure 5).

Product Design Examples

The following examples are provided as an illustration of the effect of LED and system efficiencies on product performance and component costs. The examples are based on real LEDs and typical system efficiencies found in actual lighting products.

Example #1 (see also Figure 6 below)

A lighting manufacturer wants to build a product that has a target light output of **100 lumens**. After researching different LED brands, they decide to try a 5mm LED rated at 20 mA with the following performance statistics (T_j = LED junction temperature):

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Example #1 (cont. from previous page)

Light output @ 20 mA ($T_j=75^\circ\text{C}$) = 4 lumens

LED forward voltage (V_f) @ 20 mA = 3.6 V

$$LED \text{ power @ } 20\text{mA} = I_{LED} \times V_{LED} = 0.02 \times 3.6 = 0.072 \text{ W}$$

$$\begin{aligned} LED \text{ efficacy @ } 20\text{mA} &= \frac{LED \text{ lumen output}}{LED \text{ power}} \\ &= \frac{4}{0.072} = 56 \text{ lm/W} \end{aligned}$$

The lighting product will use a diffuse acrylic cover over the LED array to reduce glare and protect the LEDs. The manufacturer tests the optical efficiency and finds that it is 80% efficient. Assuming the optical efficiency affects each LED equally, Equation 1 can be written:

$$Light \text{ output} = 4 \text{ lm} \times 80\% = 3.2 \text{ lumens per LED (lm/LED)}$$

To achieve 100 lumens, the manufacturer would need

$$\begin{aligned} N_{LED} &= \frac{100 \text{ lm}}{3.2 \text{ lm/LED}} \approx 32 \text{ LEDs} \\ \text{where } N_{LED} &= \text{number of LEDs} \end{aligned}$$

As stated above, each LED runs at 0.072 watts, and so:

$$(LED \text{ array wattage}) = 0.072 \text{ W} \times 32 \text{ LEDs} = 2.3 \text{ W}$$

The driver that will be used to control the LEDs is a linear type constant current LED driver. The electrical efficiency of the driver is tested and found to be 74%. This efficiency means that, in order to deliver 2.3 W to the LED array, the driver will draw more power from the battery as follows:

From Equation 4

$$Driver \text{ efficiency} = 74\% = \frac{P_{LED}}{P_{system}} = \frac{2.3 \text{ W}}{P_{system}}$$

$$P_{system} = \frac{2.3}{0.74} = 3.1 \text{ W}$$

3.1 W is the total system power drawn from the battery. An energy flow diagram for this scenario is shown in Figure 6 below.

Design Optimization

After reviewing the results of this example, the manufacturer may decide that more work is needed to improve the performance of the product or reduce the cost of components or product assembly.

The first place a manufacturer should look to improve their design is in the LED selection. LED quality varies widely from manufacturer to manufacturer. Many low cost LEDs have low efficacies and will always have short lifetimes regardless of the care taken in the thermal and electrical design. The materials within the LED itself are low quality and will start to degrade as soon as the LED is placed into service.

High quality LEDs are available (as of 2010) that have source efficacies > 100 lm/W. These LEDs, when handled properly, can have L70 lifetimes > 50,000 hours. Many of these LEDs are also available in high power surface mount packages, reducing the number of LEDs required to reach a certain lumen target.

Example #2 (see also Figure 7 below)

The example manufacturer finds a high power LED capable of producing more than 100 lumens. This LED is a real, 2011 commercially available LED, and the following performance statistics are **steady state light output and power measurements tested and verified by Lighting Africa researchers**:

Light output @ 375 mA = 111 lumens

LED forward voltage @ 375 mA = 2.944 V

$$LED \text{ efficacy @ } 375 \text{ mA} = \frac{LED \text{ output}}{LED \text{ power}} = \frac{111}{1.1} = 101 \text{ lm/W}$$

The manufacturer also redesigns the optics to lower the light losses from the cover and interior reflective surfaces. They are able to improve the optical efficiency from 80% to 92%. From Equation 1:

$$Light \text{ output} = 111 \text{ lm} \times 90\% = 102 \text{ lumens per LED (lm/LED)}$$

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In this case, only one LED is needed to meet the total lumen requirement (100 lumens) for the system. In addition, the manufacturer can redesign the LED driver to use a switching type constant current driver, which increases driver efficiency to 90%. From Equation 4:

$$\text{Driver efficiency} = 90\% = \frac{P_{LED}}{P_{system}} = \frac{1.1 W}{P_{system}}$$
$$P_{system} = \frac{1.1}{0.9} = 1.22 W$$

Using Equation 1, and including electronics and optical efficiencies, this example system is now:

$$\text{System Efficacy} = \frac{\text{light output (lm)}}{\text{system power (P}_{system})} = \frac{102}{1.22} = 84 \text{ lm/W}$$

By choosing a high quality LED and using efficient optics and drive electronics, the manufacturer in this example was able to reduce system power by 61%. They needed only a single LED instead of 32, and could reduce the battery capacity and solar panel size and still deliver the same performance.

System Component Costs

The increased cost of high performance LEDs is often cited as the primary reason why manufacturers choose lower quality, low cost LEDs. If, however, the total system cost is taken into account, including batteries and a solar panel (for these types of lighting products), the **materials costs can actually drop substantially for an equivalent level of performance.**

For a lighting product with an autonomous run time of 8 hours (full battery), and 4 hours per day of solar charging, the solar panel size and battery capacity can be calculated to illustrate how the efficiency affects the component costs of the complete system.

The power requirement was reduced from 3.1 W to 1.22 W. This means that the battery capacity and solar panel size can also be reduced while still maintaining

the same performance. The necessary solar panel size decreases from 5.1 watts in Example #1 to 2.0 watts in

Example #2, and the necessary battery capacity decreases from 41 watt-hours to 16 watt-hours.

Based on typical costs for these components, Lighting Africa estimates that the materials costs in Example #2 are at least 50% lower than in Example #1. Even after accounting for any added costs associated with the improved circuitry and optics, the key lesson is that optimizing efficiency can reduce overall product cost.

Performance Verification

The performance specifications and calculations used to choose components and design a product should always be verified with actual laboratory measurements. There can be large discrepancies between the performance data that an LED manufacturer lists on a data sheet and the results from real world testing. Proper laboratory testing can help validate design assumptions and ensure that a lighting product lives up to performance expectations.

Lighting Efficiency Diagrams

These Sankey diagram flow charts show the relationship between electric power and light output in off grid lighting products. The top stream (blue) represents light output, the bottom stream (red) represents electric power consumption. Arrows showing streams that split from the main lines represent optical and electronic losses in the system. The widths of the streams are proportional to the quantity of flow. The power input and system light output are shown on the right side, and the LED or LED array is represented on the left side converting electric power to visible light output. Efficacy, measured in lumens per watt, is represented in the diagram by the width of the blue line (lumens) divided by the width of the red line (power in watts); the left side of the diagram shows the starting efficacy of the LED array, and the right side shows the efficacy of the system after optical and electronic losses are taken into account.

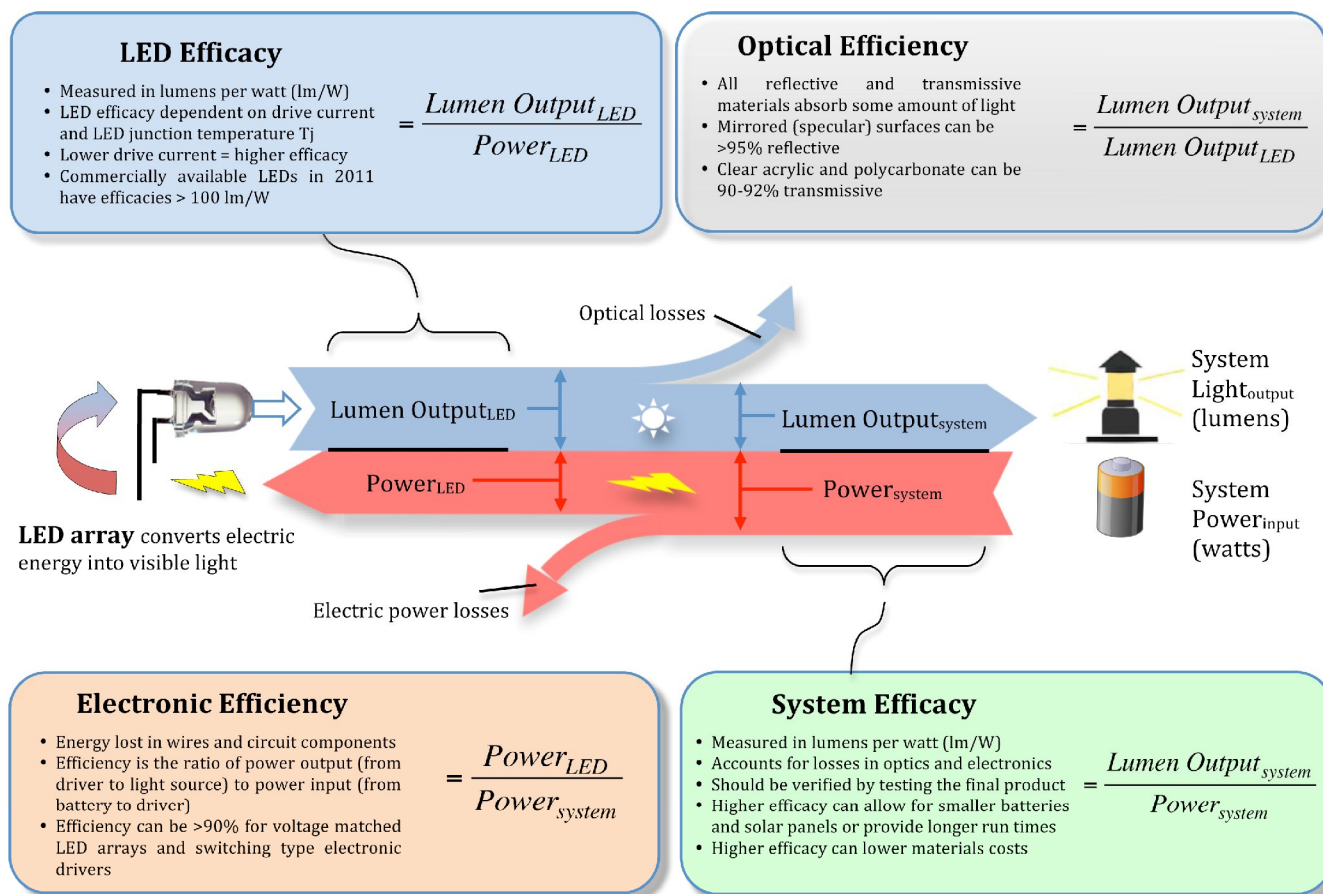


Figure 5: LED lighting system energy flow diagram

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Example #1 32 LEDs @ 4 lumens per LED
Each LED consumes 0.072 watts (=2.3 W array power)

Optical Efficiency = 0.8 = 80%
Electronic Efficiency = 0.74 = 74%

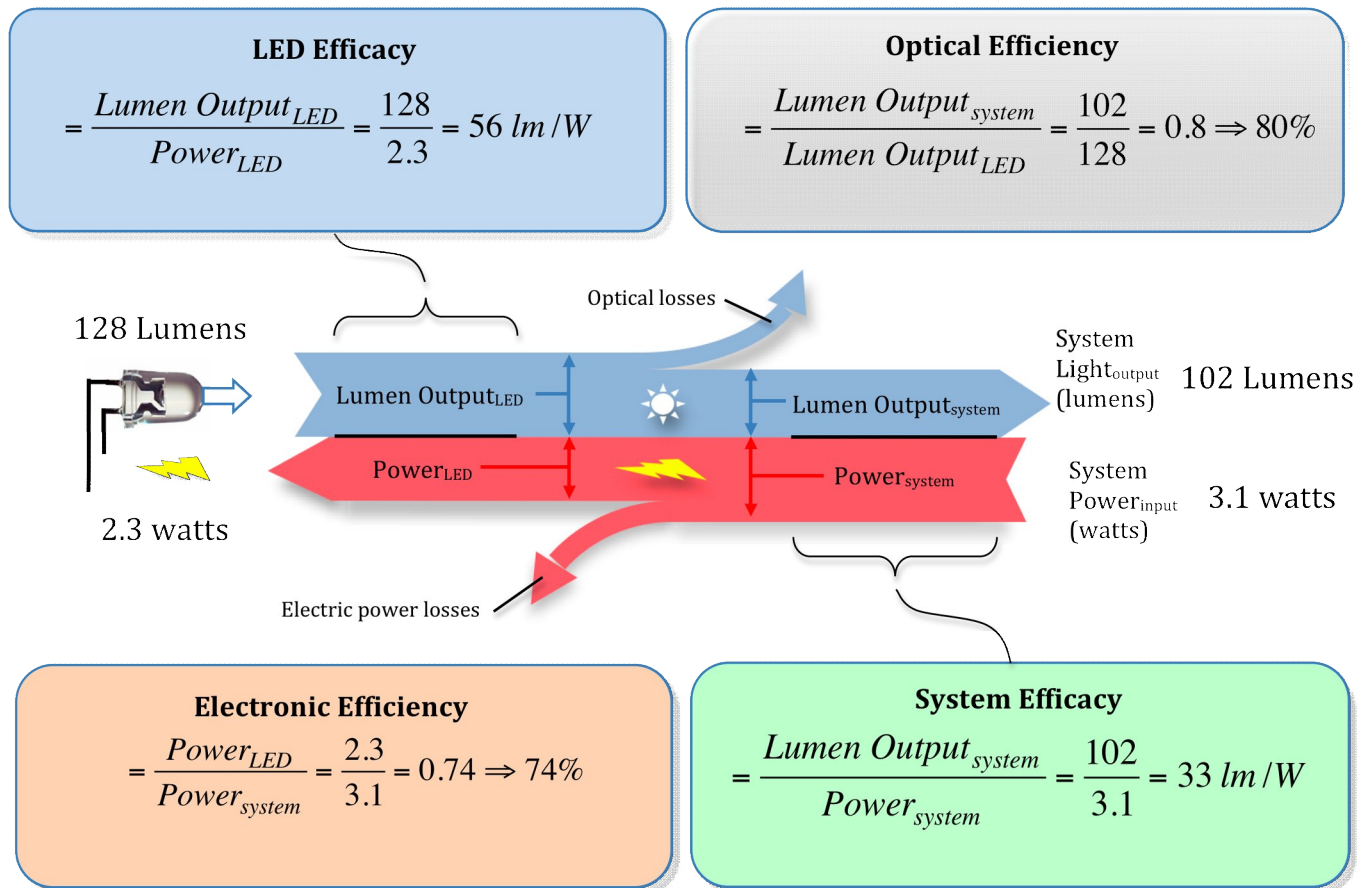


Figure 6: Theoretical LED lighting system with a 100-lumen output requirement.

The PV panel size necessary to give 4 hours of run time per solar day for this example is **5.1 watts**.

The battery capacity needed for 8 hours of operation (autonomous run time) is **41 watt-hrs**.

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Example #2 1 LED @ 111 lumens
LED consumes 1.1 watts

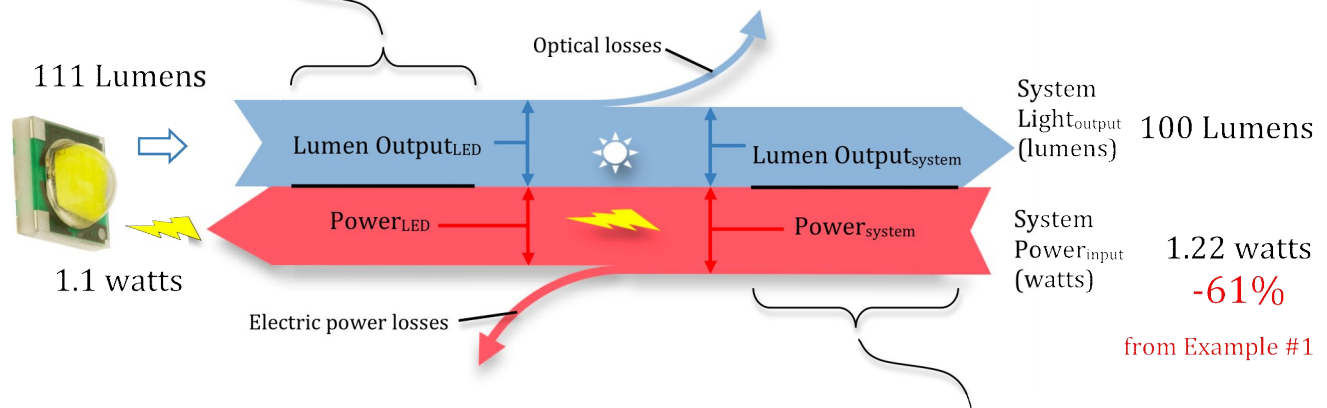
Optical Efficiency = .92 = 92%
Electronic Efficiency = .90 = 90%

LED Efficacy

$$= \frac{\text{Lumen Output}_{LED}}{\text{Power}_{LED}} = \frac{111}{1.1} = 101 \text{ lm/W}$$

Optical Efficiency

$$= \frac{\text{Lumen Output}_{system}}{\text{Lumen Output}_{LED}} = \frac{102}{111} = .9 \Rightarrow 92\%$$



Electronic Efficiency

$$= \frac{\text{Power}_{LED}}{\text{Power}_{system}} = \frac{1.1}{1.22} = .9 \Rightarrow 90\%$$

System Efficacy

$$= \frac{\text{Lumen Output}_{system}}{\text{Power}_{system}} = \frac{100}{1.22} = 84 \text{ lm/W}$$

Figure 7: LED lighting system with improved LED, optical, and electrical efficiency.

The PV panel size necessary to give 4 hours of run time per solar day for Example #2 is **2 watts**.

The battery capacity needed for 8 hours of operation (autonomous run time) is **16 watt-hrs**.