INTELLIGENT STREET LIGHTING APPLICATION FOR ELECTRIC POWER DISTRIBUTION SYSTEMS
THE BUSINESS CASE FOR SMARTGRID TECHNOLOGY

by

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Abstract

This research project builds upon previous work related to intelligent and energy efficient lighting in modern street and outdoor lighting systems. The concept of implementing modern smart grid technologies such as the proposed Street & Outdoor Lighting Intelligent Monitoring System (SOLIMS) is developed. A random sample of photocells from two municipal electric power systems is used to collect data of the actual on/off times of random photocells versus Civil Twilight (sunrise/sunset) times. A business case was developed using the data collected from the observations to support an electric utility company's implementation of SOLIMS as an alternative to current operations. The goal of the business case is to demonstrate energy and capacity savings, reduced maintenance and operating costs, and lower carbon emissions.

Key Terms – Business case, present worth, life cycle cost (LCC), annualized life cycle cost (ALCC), simple payback, energy cost, demand cost, Civil Twilight, sunrise and sunset, distribution feeder, load curve, load duration curve, probability, street lighting, energy efficiency, photocell, SOLIMS, intelligent lighting system, automation, remote control, power line communications, General Packet Radio Service, Power Line Carrier, Broadband Over Power Lines, Zigbee, NERC, FERC, DOE and EPA, municipality, utility company, asset management.

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Dedication

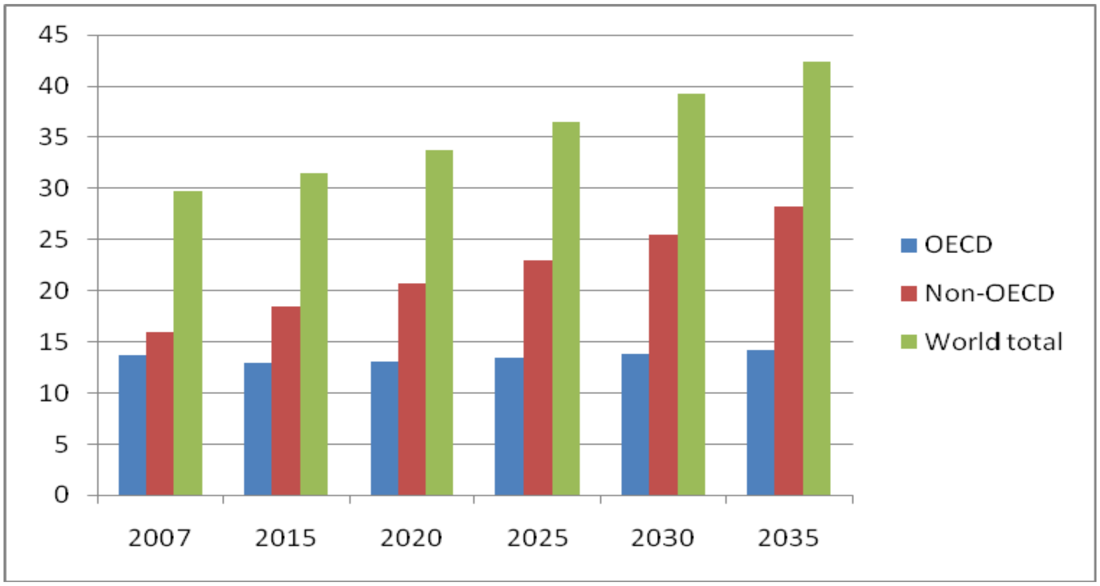
This paper is dedicated to the concept of hard work and the internal fortitude to never give up no matter how difficult the road traveled.

Chapter 1 - Introduction

A considerable opportunity currently exists for electric power companies to increase efficiency in the area street lighting. Improving electric system efficiency increases stakeholder value and recognizes the utility company as a corporate leader and innovator in reducing its Carbon footprint. For decades, street lighting has been beneficial to the public as an aid in automobile safety during nighttime driving. Street lighting also has served as a criminal deterrent in many of the world's largest cities [13]. Thirdly, utility companies have financially benefitted as street lighting serves as a source of off-peak load and revenue during light load conditions when excess generation is readily available on the grid. Utility practices concerning street lighting have changed very little over time, though it has expanded in urban and rural communities throughout the US. However, the issues of constrained energy resources and greenhouse gas emissions have played and will continue to play a critical role in the energy future of the entire world. The issues raised by the world's need to conserve energy and limit greenhouse gases such as Carbon Dioxide (CO2) will drive the need for renewable energy sources such as wind and solar, and for smart grid products that more efficiently use electric generation resources.

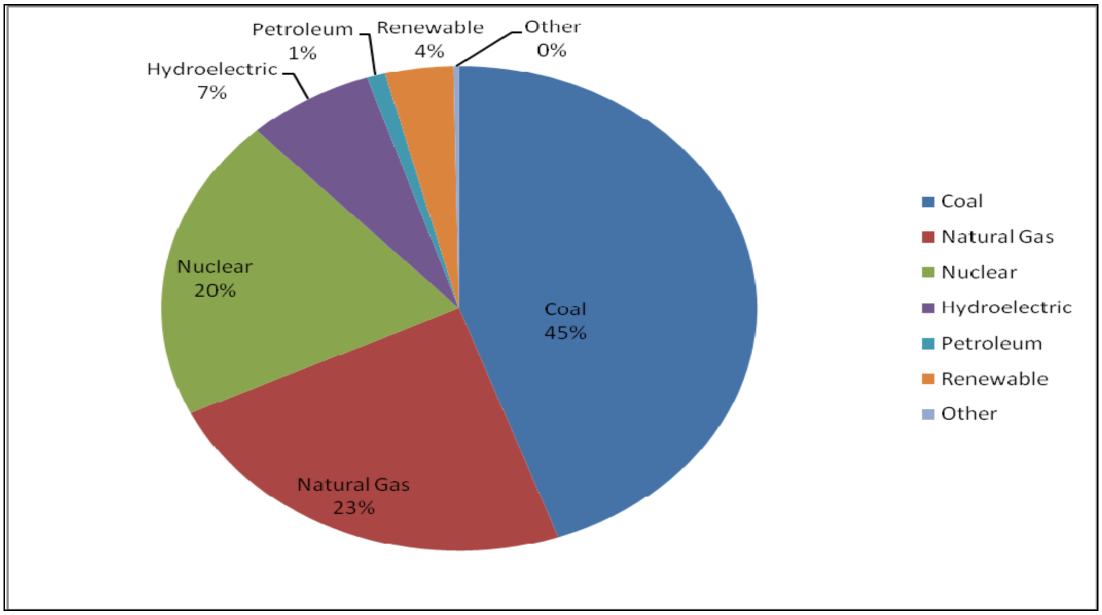
According to the US Energy Information Agency (EIA), (see Figure 1-1), world energy CO2 emissions are forecast to rise from 29.7 billion metric tons in 2007 to 33.8 billion metric tons in 2020 and 42.4 billion metric tons in 2035. This represents a growth of 43 percent over the next 25 years. In 2005, US CO2 emissions are calculated to be 5,980 metric tons. Forecasts indicate that US CO2 emissions will continue to grow at a rate of 0.2% annually through 2035. Heavy dependence on fossil fuels is expected in most non-OECD (Organization of Economic Cooperation and Development) countries. Figure 1-2 indicates that in 2009, fossil fuels accounted for 70% of electricity generation in the US and are thus, a major contributor to CO2 emissions. The North America Electric Reliability Corporation (NERC) indicates in a special assessment of the reliability of the bulk power system that several coal units are likely to retire or must be retrofitted to comply with environmental regulations [25]. This fact further complicates matters. NERC's report also indicates that up to 70 Giga-watts (GW) of coal based generation may need to be retired by as early as 2015. The report also acknowledges the aging fleet of US coal and nuclear generating plants.

Figure 1-1 World energy-related carbon dioxide emissions by fuel type, 1990-2035



Source: United States Energy Information Agency (OCED – Organization for Economic Cooperation and Development)

Figure 1-2 US Electricity Generation in 2009 - 70% fossil fuel based



Source: United States Energy Information Agency

In an effort to minimize CO2 emissions in the US, energy industry executives, state public service commissions, the President, Congress and federal agencies such as the US Department of Energy (DOE), the Environmental Protection Agency (EPA) and the Federal Energy Regulatory Commission (FERC) have aggressively promoted policies that reduce CO2 emissions and the nation's reliance on fossil-fuel-based generation moving forward. These policies include the American Reinvestment and Recovery Act of 2010 (ARRA). ARRA has allocated billions of dollars to industry and research institutions to increase the penetration of renewable generation and to develop and implement smart grid technologies. DOE has been primarily responsible for dispersing the ARRA funds, channeling most of the resources to wind and solar farm developers as well as innovations in smart grid technologies. FERC has continued to promulgate energy policies that encourage the use of renewable, demand response, demand-side management and smart grid technologies on the transmission grid through FERC Order 890 (concerning Generator Imbalance Service). Changes in Generator Imbalance Service are said to benefit intermittent resources such as wind and solar generators. Additionally, Order 890 relaxed the interconnection rules concerning interconnecting renewable energy projects to the grid. The EPA has also implemented policies such as the Clean Air Act Section 316(b), concerning cooling water intake, and the Coal Combustion Residual Rule [25]. The latter rule falls under proposed rule changes to the EPA's Resource Conservation and Recovery Act (RCRA) of 1976 that regulates the disposal of coal ash and other harmful byproducts [26].

Innovations in street lighting [15] offer a tremendous opportunity to reduce CO2 emissions, offset the imminent retirement of 70 GW of coal-fired generation, and limit the need for new generation. This all can be accomplished without compromising the safety realized from street lighting in nighttime driving and deterring criminal activity. As the cost per $MW of coal and nuclear generation continue to rise, investing in innovative ways to manage utility assets such as street lighting becomes ever more valuable. Table 1-2 below indicates that there are over 4,424,154 streetlights in the top ten most populous US cities. These street lights consume over 4,037 GWh [12] and represent over 1,106 MW of fossil fuel based generation. The nation's interstates, highways, small and medium cities, small towns, rural communities, shopping centers, and airports are not included in these figures. The City of Rocky Mount NC and the

City of Concord, NC for instance, have approximately 2,500 and 2,000 streetlights respectively. Neither of these cities have a population of over 80,000 residents.

Background and History of Street Lighting

This report presents a new and innovative approach to managing street lighting systems. The new approach is broken into two areas. First, the report focuses on using the rising and setting times of the sun to energize streetlights as opposed to the photocell which is the current practice in North America. The second area addressed by this report is the use of intelligent data collected from the street lighting system when using existing communications capabilities. The new approach provides power system operators with monitoring and control capabilities that are currently not available. When combining both the sunrise/sunset feature with modern communications, intelligent control of the street lighting system will offer significant cost savings because of reduced energy consumption and lower maintenance and operational cost. Sunrise and sunset times for all longitudes and latitudes are well recorded in the Astronomical Tables of the Naval Observatory and are precise to the clock minute.

History of Street Lighting

Historically, street lighting of roads and streets was introduced to combat crime after daylight hours. Although this is still a major justification for installing and maintaining streetlights, the chief purpose now is to reduce automobile accidents during nighttime driving [13]. There are records of attempts to light public places and crossroads occurring as long ago as the fourth century AD when wood fires were used in Jerusalem. This may only have been at times of special festivities. In the tenth century, the Arabs are said to have lit miles of streets in Cordoba [1]. Electric street lighting in Paris was in use as early as 1830 when arc lamps were used for public lighting in the Place de la Concorde. A similar lamp was mounted in Hungerford Bridge, London in 1849. However, it was not until 1870 that the efficiency of light systems improved to the point where any appreciable length of street lighting was installed. In London, a road from Westminster to Waterloo was lit by a string of forty lamps in 1879. Most all city streets of record were lit by gas flame arcs by 1913. In 1879, Joseph Swan invented the electric filament lamp. Electric lighting developed steadily; however, gas lighting was predominant due to the gas infrastructure already in place along city streets [13].

The use of electricity for street lighting became prevalent when the discharge lamp was introduced and made commercially available in 1910. Discharge lamps paved the way for the modern lamps of today. In 1932, high-pressure mercury (MBF) and low-pressure sodium lamps (LPS) were used for street lighting in Britain. Streetlights of today are primarily of the high pressure and low-pressure sodium, and metal halide types. These lights are mostly turned on and off by a photocell. Prior to the photocell, streetlights were controlled by a sundial, or solar dial time switch [14], which operates on the same principle as that proposed by SOLIMS. SOLIMS is a system that gathers intelligent data from streetlights, and communicates that data back to the central office. Data collected include, voltage, current and power consumption. This basic intelligent data is used to determine the status of groups of streetlights and identify their geographical location. SOLIMS would also send remote signals to turn streetlights on and off using Astrologic time. SOLIMS offers complete automation of the existing lighting system with minimal change in day-to-day utility company operations of line crew personnel.

Historic Street Light Sources

- Incandescent (8-20 LPW)
- Magnetic Ballast Linear Fluorescent (30-60 LPW) – 1950s and 60s
- Mercury Vapor (30-60 LPW) - Federal EPACT legislation banned as of January 1, 2008

Current Street Lights in Use

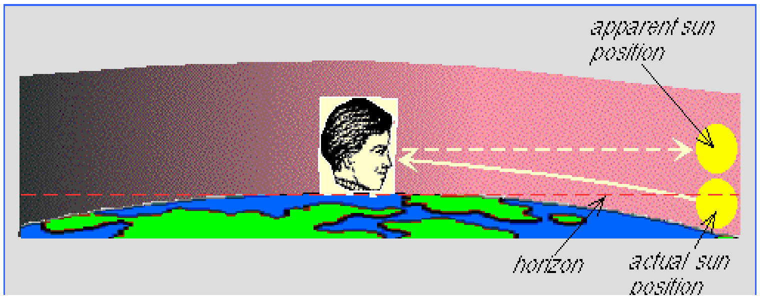
- High Pressure Sodium (80-120 LPW) – Amber-gold color and low color rendering
- Low Pressure Sodium (100-200 LPW) – Distinctive amber color
- Metal Halide (60-120 LPW) - Crisp white light and shorter life than HPS

Sunrise, Sunset and Twilight Times

There is a slight difference between sunrise/sunset times and twilight times. The distinction is critical when seriously considering implementing an Astrological scheme to control street light systems. In fact, it may be more precise to turn streetlights on or off using twilight times. The National Oceanographic and Aeronautic Administration (NOAA) define sunrise and sunset as follows:

> ***Apparent sunrise/sunset*** *- Due to atmospheric refraction, sunrise occurs shortly before the sun crosses above the horizon. Light from the sun is bent, or refracted, as it enters earth's atmosphere. See Apparent Sunrise Figure. This effect causes the apparent sunrise to be earlier than the actual sunrise. Similarly, apparent sunset occurs slightly later than actual sunset. The sunrise and sunset times reported in our calculator have been corrected for the approximate effects of atmospheric refraction [20].*

Figure 1-3 Position of the Sun



Source: http://www.srrb.noaa.gov/highlights/sunrise/glossary.html#nauticaltwilight

Before sunrise and after sunset, light from the sun is reflected from the upper atmosphere onto the Earth. These are the periods of twilight. There are specific time periods of twilight and specific times for the occurrence of sunrise and sunset. Civil Twilight, sunrise and sunset occur at different times throughout the year [21]. Civil Twilight is a term used by local governments to establish times when automobile headlights and streetlights must be illuminated. For example, a local government may require that automobile headlights be illuminated between the end of Civil Twilight in the evening and the beginning of Civil Twilight in the morning. Civil Twilight is defined to begin in the morning and to end in the evening when the center of the sun is 6° below the horizon [22]. There are also important points concerning the legal and safety ramifications of Civil Twilight associated with realizing energy efficiency. Civil Twilight occurs at a period during which ambient illumination is sufficient, under good weather conditions, for terrestrial objects to be clearly distinguished; the horizon is clearly defined and the brightest stars are visible. In the morning, before, and in the evening, after Civil Twilight, illumination is required to conduct ordinary activities [22].

Other definitions related to twilight such as “Nautical Twilight" and "Astronomical Twilight,” while not important to this discussion, should be mentioned. Nautical Twilight and Astronomical Twilight are not of issue in local government’s use of Civil Twilight. Nautical Twilight is usually used concerning Admiralty Law. Nautical Twilight begins and ends when the center of the sun is exactly 12° below the horizon. The period between the beginning of Nautical Twilight and the start of Civil Twilight makes it possible to distinguish ground objects, however, detailed outdoor operations are not possible and the horizon is not distinct. Astronomical Twilight on the other hand, occurs when the center of the sun is 18° below the horizon. During the period between Astronomical Twilight and Nautical Twilight, illumination is such that distinguishing objects is not practical [21]. An example of the difference between sunrise/sunset and Civil Twilight times in Concord, NC can be seen below in Figure 1-4 (Courtesy of www.sunrisesunset.com). In this example, we see that the difference between Civil Twilight (morning) and sunrise is twenty-five minutes. Similarly, the difference between sunset and Civil Twilight is twenty-six minutes. The total difference between Civil Twilight and sunrise/sunset in this example, for this day, is fifty-one minutes. Thus, depending on the accuracy of a photocell, fifty-one minutes of burn time can be saved daily.

Figure 1-4 Sample NOAA Calculated Sunrise, Sunset and Twilight Times

Sunrise, Sunset and Twilight Times

Location:	**Concord, NC**
Date:	**March 31, 2011**
Civil Twilight (morning):	**6:46am**
Sunrise:	**7:11am**
Sunset:	**7:42pm**
Civil Twilight (evening):	**8:08pm**

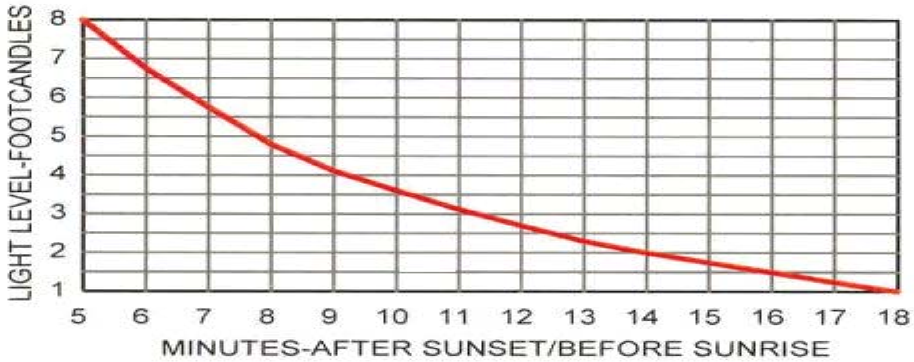
Source: http://www.srrb.noaa.gov/highlights/sunrise/sunrise.html

The Photocell Circuitry and Operation

The on/off photocell setting is characterized by a daylight curve shown in Figure 1-5. Figure 1-5 shows the relationship between light levels and time near sunrise and sunset. As can be seen in Figure 1-5 below [15], 1 foot-candle (ft-c) of light is present approximately 18 minutes after sunset or 18 minutes before sunrise. This indicates that the photocell is wasting approximately 36 minutes of energy solely due to the technology of the photocell. Another example from the figure is that 4 ft-c of light occurs about nine minutes after sunset or nine minutes before sunrise. In either case, it is clear that a device operating on the SOLIMS concept could be more accurate than the photocell. The US Occupational Health and Safety Administration's (OSHA) Standard 1917.123 concerning illumination, requires that

"…illumination in active work areas…shall be of an average minimum light intensity of 5 foot-candles…other work areas (for example, farm areas) shall be of an average minimum light intensity of 1 foot-candle except for security purposes when a minimum light intensity of 1/2 foot-candle shall be maintained…"

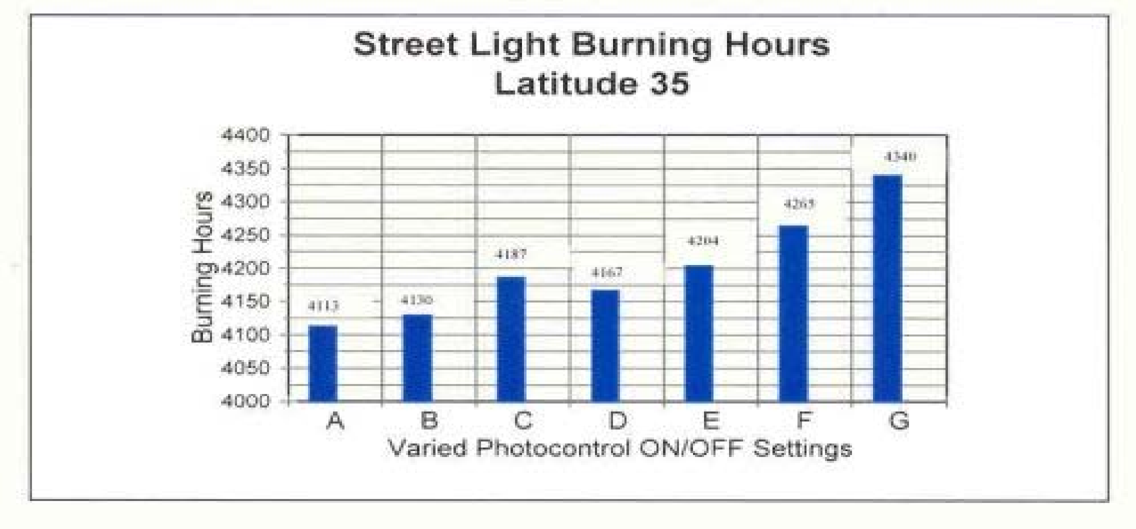
Figure 1-5 Photocell Activation (Minutes *after* Sunset vs. Minutes *before* Sunrise)



Source: http://www.americanelectriclighting.com/products/dtlphotocontrol/framework2_2.asp

Figure 1-6 highlights burn hours in a year at latitude 35E (Los Angeles, CA and Charlotte, NC) for various photocell on/off settings. This data was compiled by the Illuminating Engineering Society (IES) and taking into account: day-burners, drift, and, about five minutes per day for clouds and fog. The draft IES guide will provide more details. Figure 1-6 demonstrates that at 1 foot-candle of sun light, a photocell will cause a streetlight to burn 4113 hours (A) in a year and at 10 foot-candles, the same light will burn 4340 hours (G) in one year.

Figure 1-6 Street Light Burn Hours

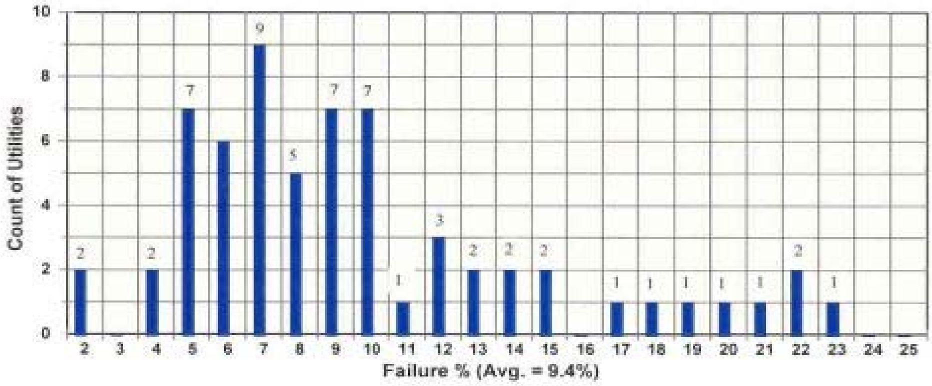


A	ON 0.8, OFF 1.0 ft-c-electronic	4,113	**E**	ON 2.6, OFF 3.1 ft-c-electronic	4,204
B	ON 1.0, OFF 1.2 ft-c-electronic	4,130	**F**	ON 1.0, OFF 3.0 ftc-electronicmechanical	4,265
C	ON 3.0, OFF 1.8 ftc-electronic	4,187	**G**	ON 2.0, OFF 10.0 ftc-electronicmechanical	4,340
D	ON 1.5, OFF 2.3 ftc-electronic	4,167			

Source: http://www.americanelectriclighting.com/products/dtlphotocontrol/framework2_2.asp

Most manufacturers state that failure rates of their electronic controls are less than 1% per year. Photocells, considered a conventional electromechanical control, generally have higher failure rates and shorter warrantees. Failure rate data were collected in one large survey of utilities and is summarized in Figure 1-7. The survey indicates that 9.4% is a more accurate failure rate [15] for photocells based on survey data.

Figure 1-7 Conventional Photocell Failure Rates (%)



Source: http://www.americanelectriclighting.com/products/dtlphotocontrol/framework2_2.asp

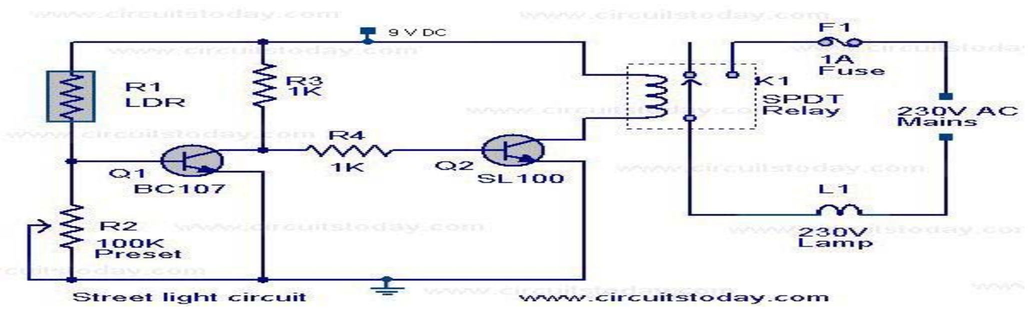
In addition, street light manufacturers indicate that photoelectric controllers are designed to ***fail with the load energized or "on".*** High failure rates translate into wasted electricity. If we apply the 9.4% failure rate to the City of Los Angeles, California, which has 242,000 streetlights [12], we can conclude that almost 24,000 streetlights are operating in a failed state and are likely burning 24 hours per day. In addition to high failure rates, another disadvantage of the photocell is that they become weathered due to outdoor conditions and this causes additional operational issues. Other disadvantages of the photocell include:

- The photocell tends to behave erratically due to dust accumulation on the sensor window
- Rain seems to cause the device to fail sporadically
- Cloudy conditions cause the photocell to switch on/off lamps even during daylight hours
- Over voltage & short circuit conditions tend to cause photocells to fail
- Internal and external thermal factors have caused failures
- It is difficult to position the photocell to true North as recommended by manufacturers

Photocell Logic

Figure 1-8 below is an electrical circuit for a photocell that automatically switches lights ON when night falls and turns OFF when the sun rises. The circuit uses a light-dependent resistor (LDR) to sense light. When light is present, the resistance of the LDR is low, thus the voltage drop across POT R2 is high. This keeps transistor Q1 ON. The collector of Q1 (BC107) is coupled to the base of Q2 (SL100), and thus Q2 will be OFF, as well as the relay. When night arrives, the resistance of the LDR will increase causing the voltage across POT R2 to decrease nearly to 0 Volts. This logic turns transistor Q1 OFF, and also turn turns Q2 ON. At this point, the relay will be energized and the lamp will glow.

Figure 1-8 Photocell Circuit Diagram

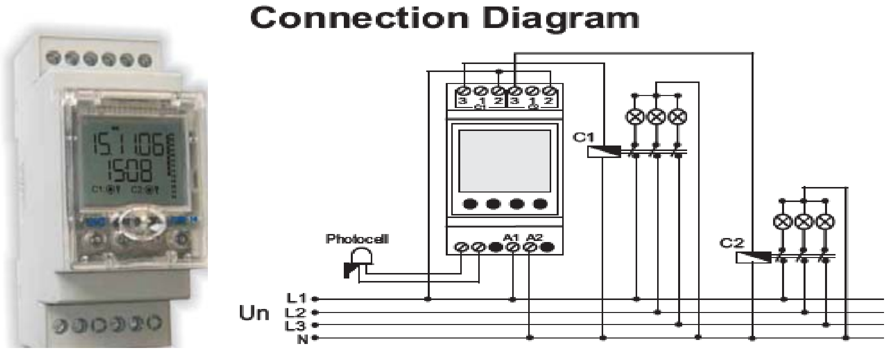


Source: http://www.circuitstoday.com/street-light-circuit#ixzz17g6PX6Nh

Figure 1-9 Typical photocell used to operate street light

Figure 1-10 is a diagram of the Astrologic Relay (DTR14), a device manufactured by *Entes*, a Turkish Company specializing in manufacturing relays and metering. The DTR14 is a relay that operates on a principle similar to that of SOLIMS, however, the *DTR14 does not provide intelligent communications back to the central office.* The DTR does employ a real clock-electronic timer that calculates sunrise and sunset times automatically based on latitude and longitude. There are two sets of contacts in the device capable of controlling up to 80 streetlights. The DTR14 also has a photocell feature. This capability will control the light based on the traditional photocell concept. The important setting for the DTR14 is the geographical location setting which requires the user to enter time zone, and latitude and longitude. This setting turns the lamp on based on Astrologic time.

Figure 1-10 *Entes* DTR 14 and connection Diagram



Impact on Energy Consumption Using the Astronomic Relay

Earlier, we hypothesized and supplied supporting information that the photocell is not the most efficient catalyst for energizing and de-energizing streetlights. On any given day, a lighting system can expect to save 1 hour of burn time using the DTR 14. Saving one hour of burn time will have a tremendous impact on energy consumption and CO2 emissions. For example, if the

DTR 14 was applied to street lights in the top ten most populous US cities, significant energy savings could be realized. Table 1-1 indicates that there are over 4.4 million streetlights in the top ten metropolitan cities in the US alone. Assuming that each streetlight burns on average 10 hours per day, over 4,037,040,525 kWh of energy can be contributed to street lighting. Improving the efficiency of street lighting systems could have a tremendous impact on reducing energy consumption and CO2 emissions in the US. These metropolitan areas could realize over $24 million in savings at current energy costs and eliminate over 237,000 metric tons of CO2 emissions.

Table 1-1 Top 10 US Metropolitan Cities and Streetlight Characteristics

Metropolitan Area	Number of Streetlights	KWh/Yr (million) - 250 Watt HPS @ 120 V	Estimated Savings 36 minute Sunrise/Sunset Technology (kWh/Yr)	Estimated Economical Savings @ $0.06/kWh	Estimated Capacity Saved (MW)	Estimated CO2 Emissions Saved (0.0005883 metric tons CO2 per kWh)
New York Metro	**1,053,838**	**961,627,175**	**96,162,718**	**$ 5,769,763**	**263**	**56,573**
Los Angeles - Long Beach, CA	**725,000**	**661,562,500**	**66,156,250**	**$ 3,969,375**	**181**	**38,920**
Chicago-Naperville-Joliet, Il	**532,321**	**485,742,913**	**48,574,291**	**$ 2,914,457**	**133**	**28,576**
Dallas - Fort Worth, TX	**336,222**	**306,802,575**	**30,680,258**	**$ 1,840,815**	**84**	**18,049**
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	**326,297**	**297,746,013**	**29,774,601**	**$ 1,786,476**	**82**	**17,516**
Houston-Sugar Land, TX	**310,237**	**283,091,263**	**28,309,126**	**$ 1,698,548**	**78**	**16,654**
Miami-ft. Lauderdale, FL	**305,975**	**279,202,188**	**27,920,219**	**$ 1,675,213**	**76**	**16,425**
Washington-Arlington-Alexandria-Montgomery County, DC-VA-MD	**296,262**	**270,339,075**	**27,033,908**	**$ 1,622,034**	**74**	**15,904**
Atlanta-Sandy Springs, GA	**287,740**	**262,562,750**	**26,256,275**	**$ 1,575,377**	**72**	**15,447**
Detroit-Warren-Livonia, MI	**250,262**	**228,364,075**	**22,836,408**	**$ 1,370,184**	**63**	**13,435**
	4,424,154	**4,037,040,525**	**403,704,053**	**$ 24,222,243**	**1,106**	**237,499**

Source: U.S. Census Bureau, CO2 Estimates, U.S. Climate Technology Cooperation Gateway Greenhouse Equivalence Calculator.

Other projected savings can be attributed to the 9.4% percent failure rate of photocells. As was mentioned earlier, when a photocell fails, it normally fails in the ON position, meaning the street light will remain ON until a utility crew replaces the photocell. Additional savings can be realized by controlling groups of lights. Controlling groups of streetlights reduces the amount of set-up time necessary for utility crews. Currently, to change a photocell, a utility crew would have to stop and set up a work area at each pole. Using a group control scheme reduces labor and maintenance costs as well as minimizing work crews' exposure to day-to-day electrical safety risks. Using Astrologic time to reduce energy consumption is not only applicable to traditional street lighting, but it can also be applied to lighting systems along interstates, in parking lots, and billboards. For example, a large food chain using Astrologic time could realize similar energy savings at all of its locations.

Communications Systems Capable of being integrated with Astrologic Timers for Intelligent Remote Control

Aside from the energy savings realized by replacing photocell technology with twilight times, more real-time information or intelligence can be extrapolated from the street lighting system if an intelligent communications system is implemented [1] [2] [3] [7] [8] [9] [16]. An intelligent street lighting system can provide the power system operator with information such as ON/OFF status, actual energy consumption, the precise ON/OFF times, and latitude and longitude of the light for maintenance purposes. There are three types of communication systems currently available for implementing an intelligent streetlight system: 1) Power Line Communications (PLC), 2) Broadband Power Line (BPL), and 3) Wireless communications. Power line communication is sometimes referred to as power line carrier (PLC), and is very similar to BPL. These systems are typically owned by the utility company, and are used to carry data on the transmission line [1] [7]. PLC's operate by impressing a modulated carrier signal on the AC transmission system and capable of using different frequency bands. However, AC transmission systems were initially setup to transmit AC power, and thus they have limited ability to operate at higher frequencies and carry communication information. BPL, on the other hand, uses PLC technology to provide broadband internet access via AC transmission power lines. In the case of the PLC, a computing device is plugged into a BPL modem and then into an electric outlet for operation [17]. An extensive BPL infrastructure is currently being developed in the US (http://smartgrid.ieee.org/ieee-smart-grid-news/2029-ieee-1901tm-broadband-power-linestandard-for-500-mbps-communications) [3]. Both PLC and BPL offer solutions for an intelligent remote controlled street lighting system.

Wireless technology is also an option that should be seriously considered when implementing an intelligent street lighting system. General Packet Radio Service (GPRS) [1] [2] [7] [11] used in concert with Zigbee [1] [3] technology is a solid option for implementing a wireless street lighting system [1]. GPRS is a packet-oriented mobile data service on the cellular communication system for global system mobile communications (GSM). The service is available to users in most countries around the world. Unlike traditional circuit switching communications, GPRS is not a guaranteed service. In circuit switching, a certain quality of service (QoS) is guaranteed for the communication connection. It provides moderate data transmission speed by using unused time division multiple access (TDMA) channels [18]. GPRS is generally used for longer distance communication applications where data from the field is communicated back to the central office. Zigbee is a growing communication protocol that can communicate up to 100 meters. To be used in street lighting applications, data concentrators would need to be installed to gather data from the mini-hubs that use Zigbee communications. Once data is gathered from the Zigbee concentrator, then GPRS can be used to transmit the data over longer distances. Thus, multiple communications alternatives exist to support implementing an intelligent street lighting system; both wireless and hard-wired systems can be deployed. This report proposes a unique and innovative Street & Outdoor Lighting Intelligent Management System (SOLIMS) that will have the capability of using twilight times to control streetlights. In order to be deployed, SOLIMS must be implemented using one of the three communications systems. The system will provide much needed intelligent information that to the operator that is currently not available.

Chapter 2 - Opportunity to Improve Efficiency and Implement Intelligent Technology

Chapter 1 highlighted opportunities to increase energy efficiency and take advantage of automation in street lighting [15] [16] by using Astrological time to control streetlights. In addition, the concept of adding remote communications was discussed. Chapter 1 also highlighted the fact that street lighting in the top ten populous US cities use over 4,037 GWh and has a capacity of over 1,106 MW. Street lighting systems typically have a very good load factor between 33 and 42% since they operate for 8-12 hours during the night [15]. The estimates presented in [15] do not account for street lighting along the nation's interstates, that stretch several thousand miles from the east coast to the west coast, both north and south, as well as connecting major cities to smaller municipalities and to rural communities. This report estimates that the numbers presented in [15] represents less than 20% of the street lighting in the US. Actual numbers are not readily available.

The business case developed in this report focuses on energy savings realized from innovative approaches to street lighting as compared to the current practice. Secondly, this report focuses on the energy savings realized when comparing actual on/off times given current photocell technology relative to Civil Twilight or Astrological time. The goal of this report is to demonstrate the energy savings that can be realized by utility companies (investor owned, municipal and cooperative), and other large users of street and outdoor lighting. Furthermore, the goal is to develop a solid business case to support a philosophical change in street lighting practices currently employed by utility companies. The business case is based on retrofitting an existing street lighting system with intelligent controls [1] [2] [3] [8] and available smart grid technologies that turn street lights on and off based on Civil Twilight times. The business case will demonstrate the economic feasibility [6] [7] [10] [12] for a utility company to move from its traditional lighting practices to more energy efficient and modern operations. A classical Life Cycle Cost (LCC) analysis will be used to meet the stated goal.

Street lighting - Off-peak load and revenue for the power company

While the primary purpose of street lighting is safety on two fronts, a secondary purpose for street lighting is that it provides off-peak load for utility companies during light load conditions. Most utility companies have excess generation capacity during off-peak hours. Daytime load is normally higher than nighttime and early morning load. During nighttime hours, residential customers are usually asleep and load levels are thus lower [20]. Street lighting revenue is economically beneficial to utility companies given that generating units are usually constrained by their minimum and maximum output characteristics or by available human resources to bring a plant on or off line.

Under ideal conditions, a utility company would like to run the majority of its generating units at peak efficiency and peak output levels [20]. The unit commitment problem clearly states that it is desirous to commit only those units necessary to meet system load and leave those units running. However, depending upon the economics of a particular generating unit, it may be more economical to take the unit off line. In either case, turning units on and off is an economical decision made using sound unit commitment algorithms [20]. In addition, ramping units up and down on regular intervals can be economically disadvantageous to a utility company as most generating units are most efficient when they reach their optimal set point and remain at a flat MW output.

Electric Power Company Load and Duration Curves

The traditional load curve offers key insight into how street lighting affects day-to-day power system operations. Table 2-1 and Figure 2-1 present a pseudo but typical utility company load curve [19]. This curve characterizes residential, commercial, industrial and street lighting load. Figure 2-1 shows the individual load curves and the aggregate load curve for the entire pseudo power system. In this case, the system has a peak load of 2,200 MW with the peak occurring in the evening around 1700. Two other large increases in load also occur throughout the day and are not as high as the overall daily peak but are quite obvious in Figure 2-1. One of the lower peaks occurs in the late evening from 1800 to 1930. This peak is usually caused by residential customers coming home, turning on lights, cooking and doing those things typical at the end of the day in a home. The other large increase in load is also due to residential customers and it occurs in the morning hours from about 0600 until 0900.

Figure 2-1 Load Profile for Typical Electric Distribution Feeder

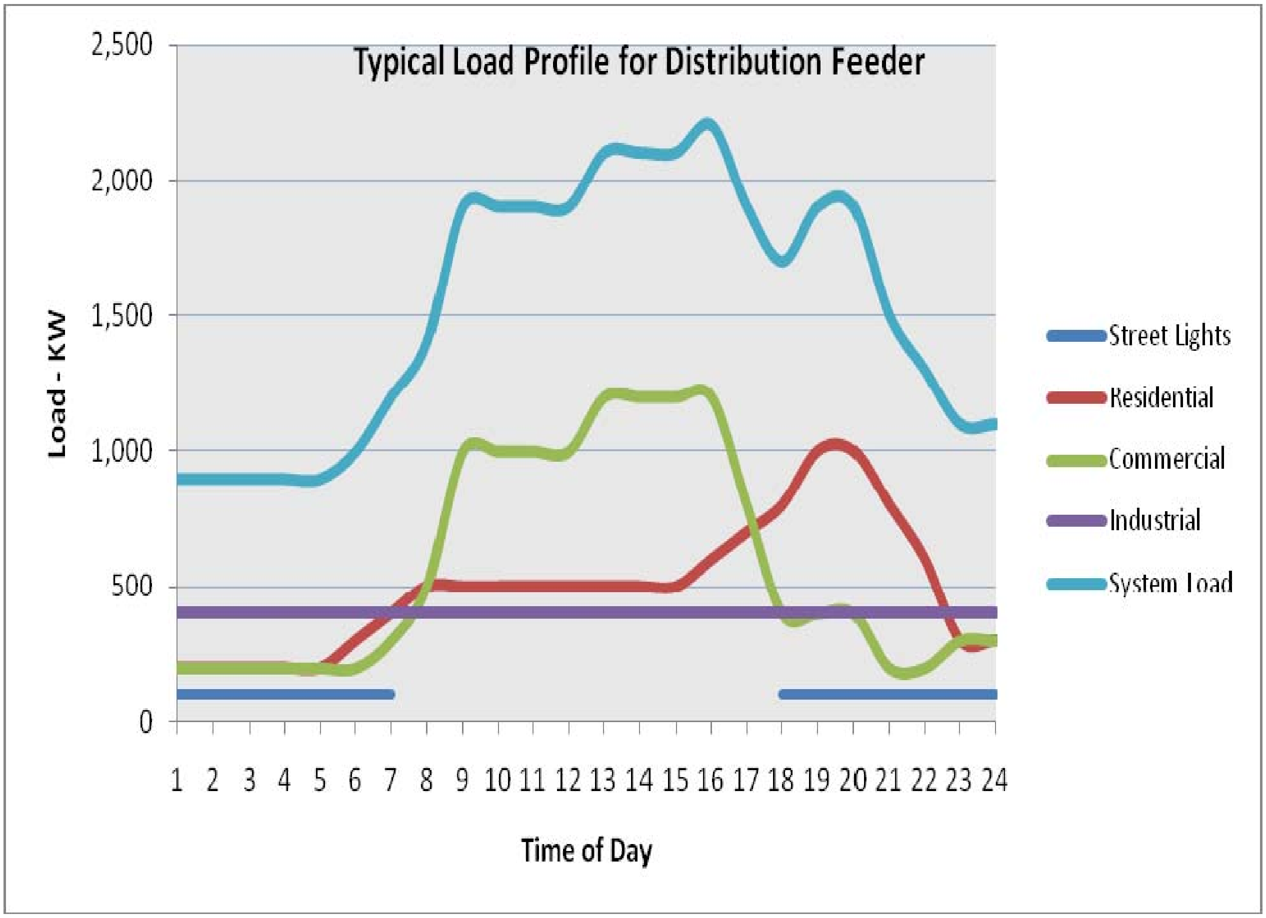


Table 2-1 Pseudo Load Data for Load Curve

Hour	Street Lights	Residential	Commercial	Industrial	System Load
0	100	200	200	400	800
1	100	200	200	400	800
2	100	200	200	400	800
3	100	200	200	400	800
4	100	200	200	400	800
5	100	200	200	400	800
6	100	300	200	400	900
7	100	400	300	400	1,100
8		500	500	400	1,400
9		500	1,000	400	1,900
10		500	1,000	400	1,900
11		500	1,000	400	1,900
12		500	1,000	400	1,900
13		500	1,200	400	2,100
14		500	1,200	400	2,100
15		500	1,200	400	2,100
16		600	1,200	400	2,200
17		700	800	400	1,900
18	100	800	400	400	1,600
19	100	1,000	400	400	1,800
20	100	1,000	400	400	1,800
21	100	800	200	400	1,400
22	100	600	200	400	1,200
23	100	300	300	400	1,000
24	100	300	300	400	1,000

Source: Electric Power Distribution System Engineering, Turan Goen, 1986.

Street Lighting and its Impact on the Load Curve

Using twilight times as a catalyst as opposed to the current practice of photocells can save utility companies between fifteen and thirty minutes of burn time around twilight periods without sacrificing public safety. For example, if we examine the load curve of the pseudo power system presented in Figure 2-2, and reduce the lighting load for thirty minutes in hour ending 0700 and hour ending 1800, the resultant impact to the load curve is observed. The effective energy savings is the integration of the time that the streetlights are not burning. For the morning hour, the street lights would not burn from 0730 until 0800, thus the street light would shut off at 0730. In the evening, the streetlights would not burn from 1800 until 1830. Integrating the thirty-minute time intervals in which the lights do not burn, and then summing the results for both periods, we see an approximate savings of one hour of burn time or 100 kWh for the day. Below are the equations used for integration, and thus used to determine energy savings.

$$\int_{0730}^{0800} \mathrm{Pt}\,\mathrm{dt} + \int_{1800}^{1830} \mathrm{Pt}\,\mathrm{dt} = \text{Projected Energy Savings}$$

Where:

P = kW demand of the street light system (which from our pseudo system above is 100 kW)

t = burn time saved by when using proposed sunrise/sunset, in this case t = 0.5hrs

The projected energy savings for the pseudo power system are as follows:

*Energy Savings = 100 kW * 0.5 hours + 100*0.5hours = 100 kWh for one day*

Figure 2-2 shows the new load curve using twilight times superimposed over the old load curve. We clearly see the impact of using the twilight time as a catalyst. During the morning peak, turning the streetlight off earlier reduces the slope of the morning load rise. Typically, in meeting the morning peak, power system operators bring on nearly all available generating resources over a short period of time. This typically occurs over a one and a half hour period to meet the morning peak load. During the wintertime, this can be especially challenging as morning peaks are often higher than evening peaks due to the colder temperatures in the morning. “Chasing the peak” is always a critical time in the control room as all available resources are in use and reserves are minimal. The most expensive units or “peaking units” are brought on line to meet the peak in most cases. The alternative is to drop load or blackout portions of the power system to prevent cascading outages. Streetlights have a demand of 100 % of the connected load when energized; this demand on the system at times may coincide with the winter peak if it occurs during the morning hours. In many ways using twilight time as a catalyst for controlling streetlights serves as a resource to the power system operator, aiding in balancing load and generation under peak conditions.

The impact on the evening peak may not be as great as the impact on the morning peak for capacity purposes. However, the energy savings is very nearly the same. In the evening, power system load tapers off around 1630 and rises again around 1800-1830. We must remember that twilight time's change daily due to the earth's rotation and orbit around the sun. Thus, during daylight savings time, the other significant load increases occur during the evening and can be as late as 2030 or later depending on the time of year.

Figure 2-2 Impact on Typical Load Curve

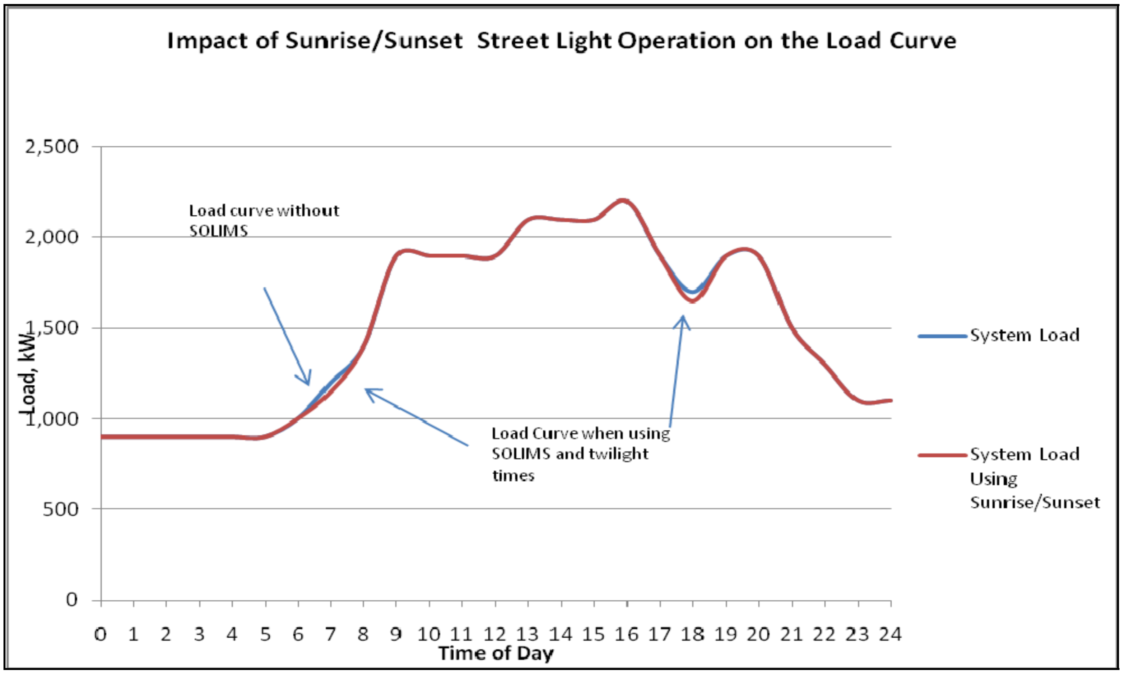
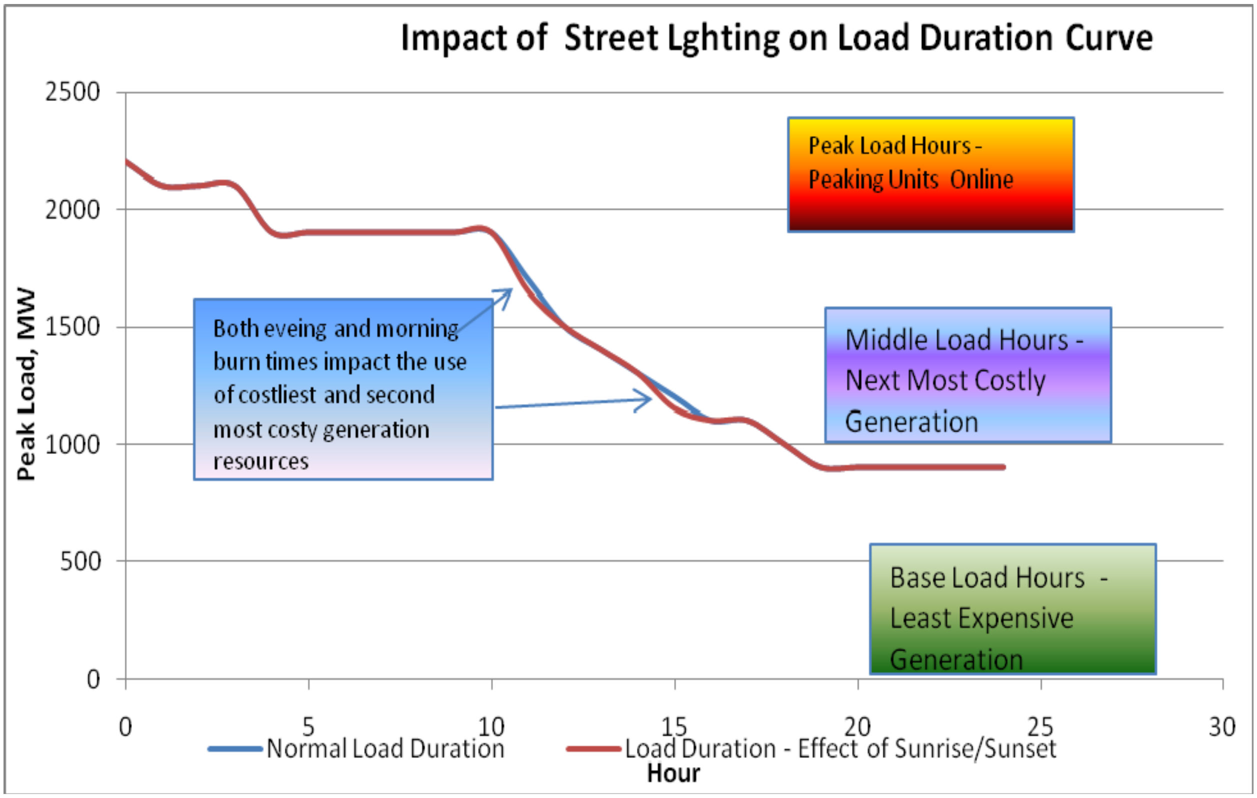


Figure 2-3 is the load duration curve for our pseudo power system. The load duration curve is developed by rearranging all load values from highest to lowest and then connecting them by a curve [18]. Load duration curves can be developed for daily, weekly, monthly, or annual load durations. The curve in Figure 2-3 is that of a daily load duration curve with 24 hourly load values. Reducing the burn time of street lights has an impact on the load duration curve. Essentially, the number of MWh requried of the various generation blocks is slightly lowered. The most important observation in Figure 2-3 is that energy saved by implementing a modern approach to street lighting reduces the production output of the most expensive generating units. The peak load hours and the middle load hours identified in Figure 2-3, require bringing on the more costly generating units. Clearly, street lighing has an impact on the load duration curve from our analyis, however, it is difficult to quantify the impact without perfroming a complex production cost analysis [17] that would be required to cover short periods of time.

Figure 2-3 Impact on the Load Duration Curve



Chapter 3 - Experimental Results of Actual Photocells from Municipal Power Companies

To test the hypothesis that using Civil Twilight time is valid; a random sample of photocells from two municipal power systems was tested. Rocky Mount Public Utilities Department (RMPUD) and the City of Concord Electric (CCE) volunteered to provide a random sample of photocells for testing. Both utilities are members of the American Public Power Association. RPMUD is located in Eastern North Carolina, and serves just over 30,000 customers with non-coincident peak load of 160 MW. It is estimated that RMPUD has nearly 2,500 streetlights on its system with a load of 625 kW (or 0.39% of system peak load), when assuming the typical light is a standard 250 watt High Pressure Sodium light. CCE on the other hand, serves approximately 26,000 customers with a non-coincident peak load of just over 190 MW with a little over 2,000 streetlights. Using a similar method for estimating demand as with RMPUD above, CCE's streetlights have a demand of 500 kW and represent approximately 0.26% of peak load. Both utilities provided two 120-volt photocells that were randomly selected by line crew personnel.

The photocells represent a sample of four out of approximately 4,500 photocells in use for the two systems combined. Each photocell was tested using an *Utilitech 70-Watt, 120 volt, Aluminum Dusk-to-Dawn Security Light* (see Figure 3-1). Each photocell was placed in the lamp for two days to sample and measure [23] the time the photocell turned the lamp on as compared to local Civil Twilight time. The following procedure was used to collect the time data.

1. The *Utilitech* 70-watt lamp was wired to a 120-volt electric plug using #10 copper wire.
2. Each photocell sample was manually installed into the lamp with the eye of the photocell pointing north as recommended by the manufacturer.
3. Once the sample photocell was installed, manual observation of the lamp began approximately 20 minutes prior to NOAA calculated sunrise and sunset times.
4. Once the lamp was energized or de-energized, the approximate time was recorded in Table 4-1 using time from an iPhone that is synchronized with satellite time.
5. Step 4 above was repeated for each observation and recorded in Table 3-1.

Figure 3-1 Utilitech70 Watt HPS Light (Also shown are the four photocells donated by the City of Rocky Mount and the City of Concord in blue and black)

The time recorded from the procedure above was used to calculate estimated energy savings for implementing SOLIMS. Each of the photocells can be viewed as one of four independent variables. A classic statistical estimator was used to determine the average value of estimated times used to determine energy savings.

$$X = (1/N) \sum_{n=1}^{N} Xn \qquad \text{(estimated average of N samples)}$$

Where,

N = number of samples
Xn = values of identically distributed, random variables (Xn are independent random variables)

Using the equation above [23], it was determined that the average time that street light burned prior to Civil Twilight is 23 minutes for each evening and morning recording. Thus, the observations led to the conclusion that the sample of four photocells were burning on average approximately 46 minutes per day (23 * 2) before the beginning and ending of Civil Twilight.

Table 3-1 Measured Data from Sample Observations of Photocells

Observation	**Twilight (Morning - Evening)**	**Time Light Came – ON**	**Actual Difference between Twilight and Photocell ON/OFF**	**Observed Weather Conditions**
Observation 1 - Morning 3/18	7:04	7:27	0:23	Sunny/Clear
Observation 2 - Evening 3/18	7:58	7:47	0:11	Clear
Observation 3 - Morning 3/19	7:03	7:40	0:37	Cloudy
Observation 4 - Evening 3/19	7:58	7:41	0:17	Clear
Observation 5 - Morning 3/20	7:02	7:30	0:28	Cloudy
Observation 6 -Evening 3/20	7:58	7:39	0:19	Clear
Observation 7 - Evening3/21	7:59	7:37	0:22	Cloudy
Observation 8 - Evening 3/22	8:00	7:40	0:20	Clear
Observation 9 - Evening 3/23	8:01	7:43	0:18	Sunny/Clear
Observation 10 - Evening 3/23	8:02	7:36	0:26	Sunny/Clear
Observation 11 - Evening 3/27	8:04	7:32	0:32	Clear
Observation 12 - Evening 3/29	8:06	7:35	0:31	Clear
		Estimated Time Saved	**0:46 minutes (Average burn time without weighting)**	

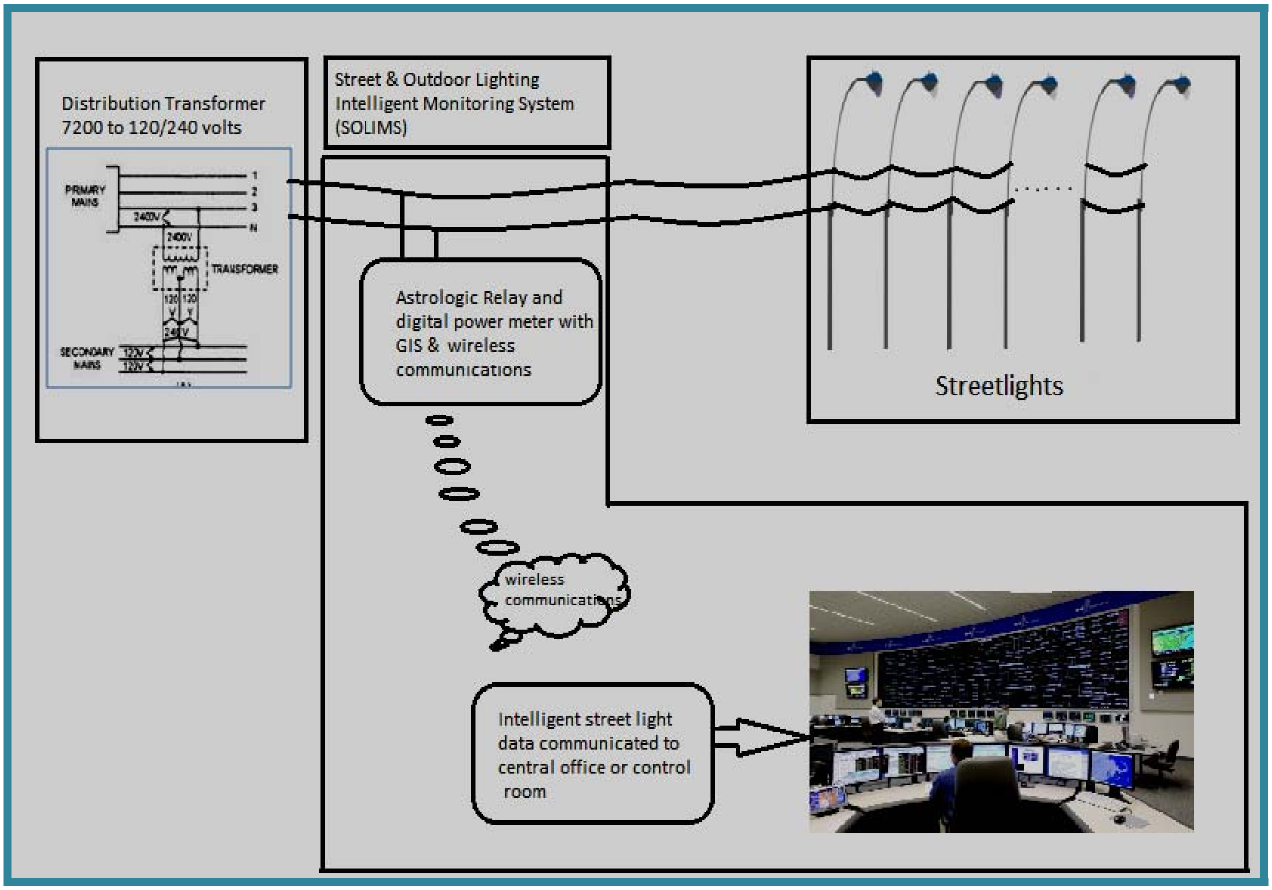
Twelve observations were taken and data was collected for analysis purposes. Nine samples were taken in the evening and three samples were taken in the morning. One observation from the data recordings is that the morning samples had a greater difference between twilight time and the actual time the light turned off. In future work, a more precise test system should be used to collect data between morning and evening periods to further observe the difference between morning and evening data recordings.

Chapter 4 - Business Case for Altering the Way Power Companies Manage Street lighting Systems

The business case for a utility company to migrate from its existing practices is based on energy (kWh) savings, lower maintenance cost and a need to offset escalating energy prices in the future. To achieve the 46 minutes of burn time estimated above, a utility company would need to integrate a system similar to SOLIMS (see Figure 4.1). The SOLIMS system could be installed on the low side of a typical distribution transformer and energized at 120 volts (7200/120/240V). The system would be designed such that a typical utility line crew of two men with a bucket truck could install the system with little, if any, additional skill than currently possessed. The system consists of the following components that will need to be integrated into the day-to-day operations of the power system for it to be installed:

- Astrologic software that calculates twilight times
- A relay capable of receiving ON/OFF signals from Astrologic software
- Relay with group lighting control capability
- Communication system (Broadband, Powerline Carrier or Wireless – GPRS)
- Intelligence - Metering of voltage, current and power that is communicated to the central office where a custom software platform continually analyzes street light system data.
- Software in the central control office monitors and creates reports detailing status and need for maintenance on groups of streetlights.

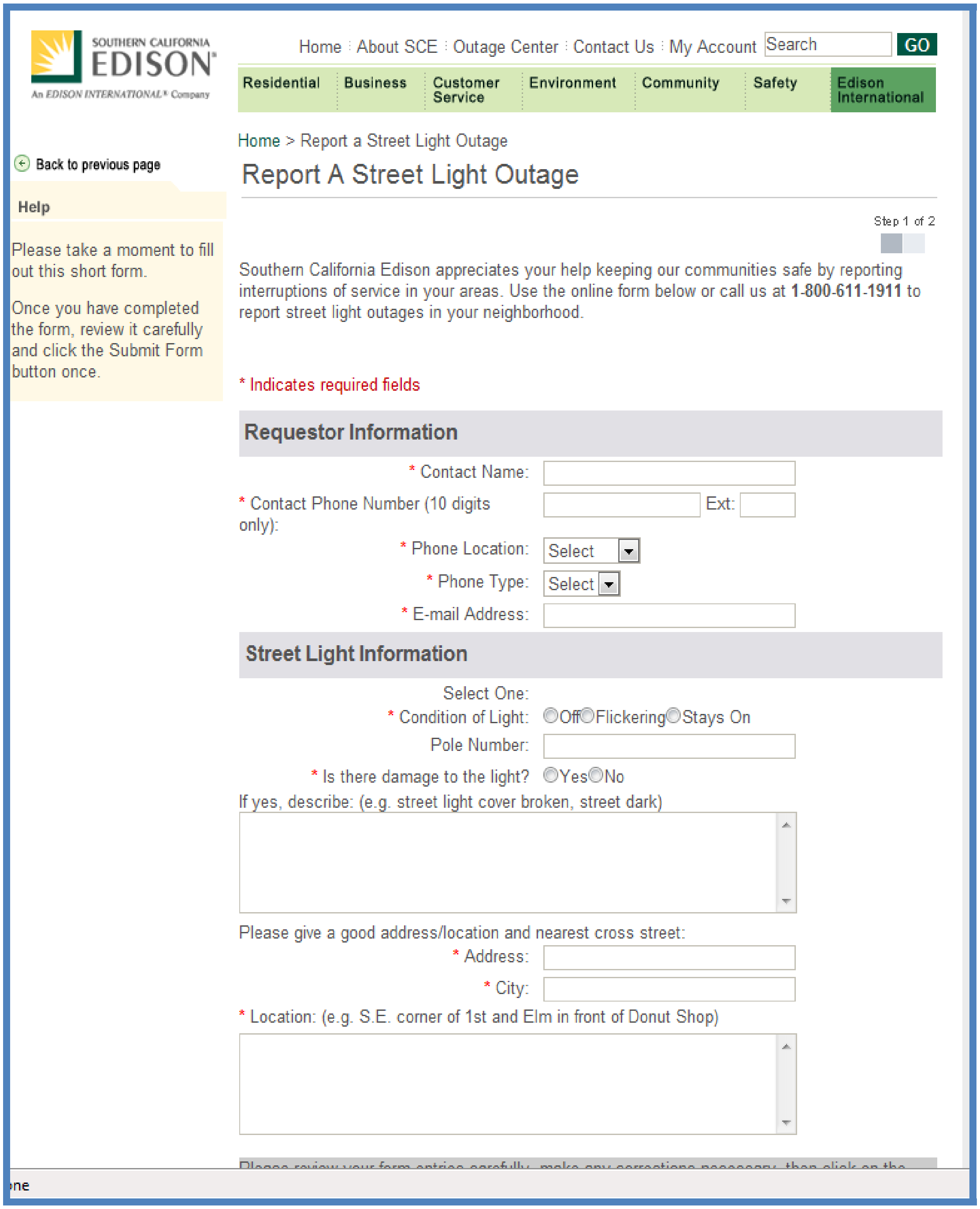
Figure 4-1 Street & Outdoor Lighting Intelligent Monitoring System



Each SOLIMS is capable of controlling as many as 80 streetlights, with a typical installation controlling approximately 40 lights in a group control scheme. The number of lights to be controlled is limited by the voltage drop [4] [9] resulting from the light's distance to the source. Some roadway intersections or highway exit ramps may be able to accommodate up to 80 lights since these roads fork into multiple directions and each string of lights could be controlled by a single controller. Once developed, the cost of the system is estimated to be $2500 - $2700 with minimal annual maintenance cost. Annual maintenance for the SOLIMS is mostly related to maintenance of the relay in the field and updates to the SOLIMS software platform. The back office software would provide visualization and location capabilities of street light status using a utility company's existing GIS capabilities.

An economic analysis was performed on the RMPUD lighting system, primarily because the system had more lights. The analysis is based on the assumption that RMPUD has approximately 2,500 streetlights owned and operated by the city. We also considered a typical 250 watt HPS light for our economic analysis. Under normal operating conditions, the HPS lights would use approximately 1,825,000 kWh annually for RMPUD. Additionally, our analysis assumes that 9% of the streetlights fail annually under current operations. When these failures occur, the photocell system is designed to fail in the ON position, and thus burning 24/7 using an estimated 486,000 kWh annually for our test system. Given current utility practices and the lack of intelligence in street lighting infrastructure, a street light may burn indefinitely unless the malfunction is noticed and reported by a customer or Good Samaritan. For instance, Southern California Edison has a link on its website for customers to click and fill out a form (see Figure 4-2 below) indicating that a streetlight has malfunctioned. Most other utility companies have similar links on their web pages. The webpage counts on individuals taking the time to navigate to the company's website and complete the necessary forms. Atlantic City Electric, on its website, asks customers to locate pole numbers to offer a precise location for the power company when reporting street light outages online. One can only imagine the Good Samaritan stopping on a dangerous highway to write down a distribution pole number. However, this is the antiquated system currently in place. The system is wrought with inefficiency and public safety concerns.

Figure 4-2 Typical Utility Street Light Outage Reporting Form



Home > Report a Street Light Outage

Report A Street Light Outage

Help

Please take a moment to fill out this short form.

Once you have completed the form, review it carefully and click the Submit Form button once.

Southern California Edison appreciates your help keeping our communities safe by reporting interruptions of service in your areas. Use the online form below or call us at **1-800-611-1911** to report street light outages in your neighborhood.

* Indicates required fields

Requestor Information

* Contact Name:
* Contact Phone Number (10 digits only): Ext:
* Phone Location: Select
* Phone Type: Select
* E-mail Address:

Street Light Information

Select One:
* Condition of Light: ○Off ○Flickering ○Stays On
Pole Number:
* Is there damage to the light? ○Yes ○No
If yes, describe: (e.g. street light cover broken, street dark)

Please give a good address/location and nearest cross street:
* Address:
* City:
* Location: (e.g. S.E. corner of 1st and Elm in front of Donut Shop)

Source: https://www.sce.com/forms/ReportStreetLightOutage.aspx

The dependence upon a customer reporting outages would be eliminated when implementing SOLIMS. We further assume that SOLIMS will reduce daily burn time by 46 minutes based on data recorded from sample photocells. FERC FORM 1 was used to determine the estimated energy cost and demand charges. Table 4-1 provides an overview of key assumptions used in the LCC analysis.

Table 4-1 Key Assumptions Used to Develop the Business Case for SOLIMS

City of Rocky Mount	
Estimated peak load	160 MW
Number of Lamps (250 watt)	2500
Estimated annual failure rates of photocells @ 9%	225
Estimated Annual kWh (including failures) – Normal	2,286,000
Estimated Annual kWh - Due to failures	486,000
Estimated Annual kWh using SOLIMS	1,626,750
Estimated Energy Cost $/kWh	$0.03 – $0.05
Discount Rate	8%
Inflation Rate	4.0%

An LCC analysis was performed using the data and assumptions shown in Table 4-1 above. The LCC analysis was performed over the expected 20-year life of the SOLIMS systems. A classic LCC analysis considers the total cost of owning and operating a system over its expected life. Utility companies often use LCC to compare two alternatives for investing purposes. In this report, LCC is used to compare the cost of installing SOLIMS versus the alternative of continuing current operations. The advantage of an LCC analysis is that total costs for both alternatives are referred to a single point in time for comparison purposes [8]. Additional assumptions are that that each SOLIMS controls 40 streetlights. Sixty-three (SOLIMS) are required at a cost of $2,700 each to completely modernize the system. Installation and set up cost are included in the $2,700. The estimated capital investment required by the city to modernize its street lighting system is $170,100. Results of the LCC analysis are presented in Tables 4-2 and 4-3 below. Table 4-2 assumes the cost of energy is $0.03 per kWh and Table 4-3 assumes the cost of energy is $0.05 per kWh.

Table 4-2 Life Cycle Costing with Present Worth – Cost of Energy @ $0.03/kWh

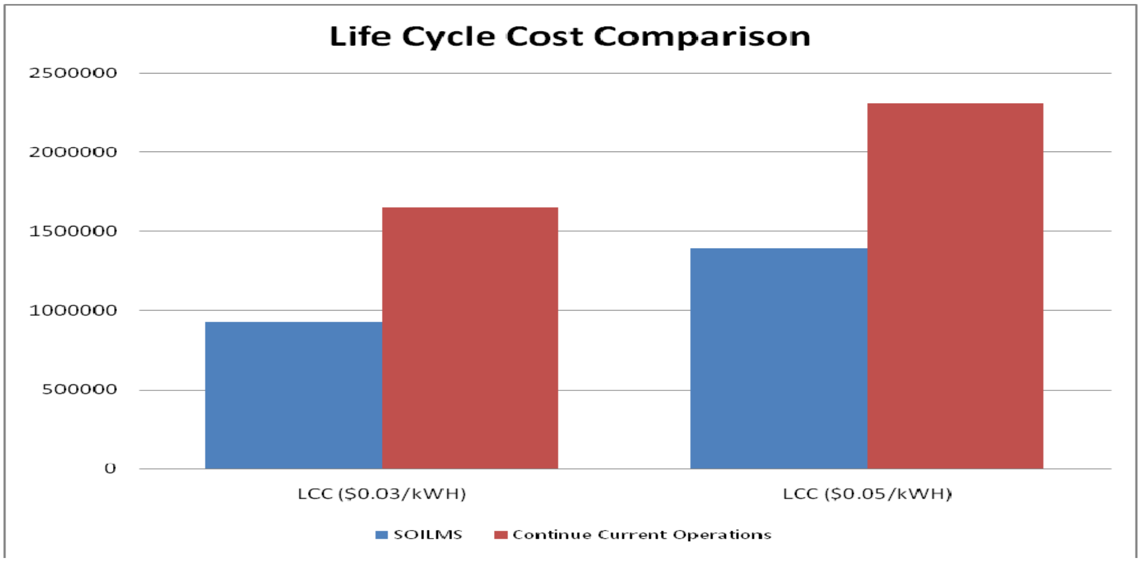
	SOLIMS			**Continue Current Operation**	
	Capital Cost ($)	**Present Worth ($)**		**Capital Cost ($)**	**Present Worth ($)**
Capital Cost	170,100	170,100		-	-
Energy Cost ($0.03/kwh)	48,803	698,230		54,000	772,592
Maintenance Cost	3,938	56,335		46,875	670,653
Cost of Photocell Failure (24 hour burn time)				14,580	208,600
LCC		**924,665**			**1,651,845**
ALCC		**64,629**			**115,455**

Table 4-3 Life Cycle Costing with Present Worth – Cost of Energy @ $0.05/kWh

	SOLIMS			**Continue Current Operation**	
	Capital Cost ($)	**Present Worth ($)**		**Capital Cost ($)**	**Present Worth ($)**
Capital Cost	170,100	170,100		-	-
Energy Cost ($0.05/kwh)	81,338	1,163,717		90,000	1,287,653
Maintenance Cost	3,938	56,335		46,875	670,653
Cost of Photocell Failure (24 hour burn time)				24,300	347,666
LCC		**1,390,151**			**2,305,972**
ALCC		**97,164**			**161,175**

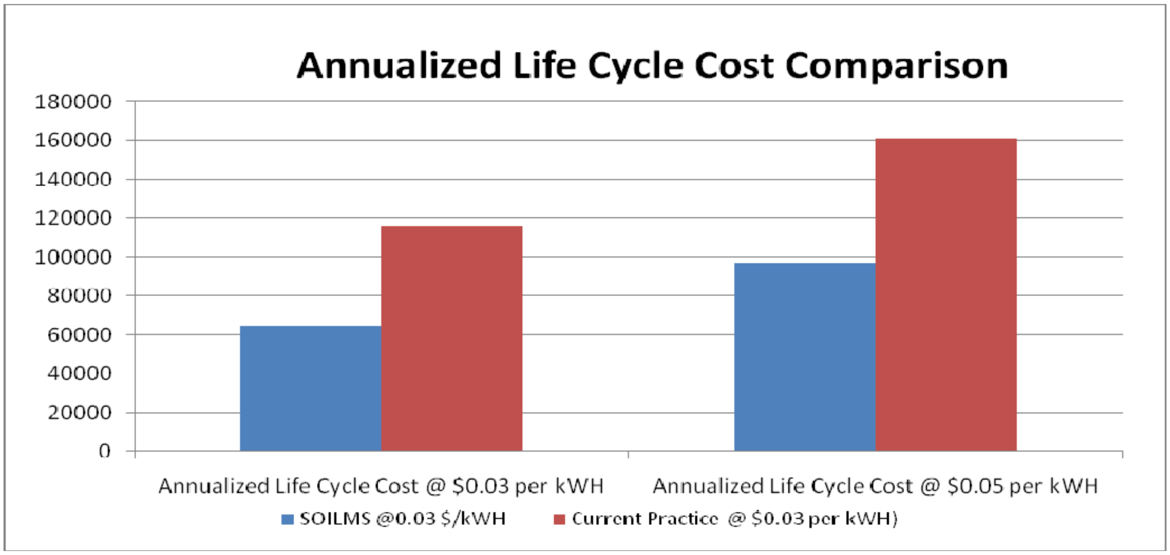
Under the $0.03 kWh scenario, the LCC over the 20 year expected life of the system is determined to be $924,665. In the alternative, the LCC for continuing current operations is $1.79 Million. In the $0.03 kWh case, SOLIMS can be operated at 56% of the alternative to continue current operations representing a difference of $727,180.

Figure 4-3 Life Cycle Cost Comparison



If we increase the cost of energy from $0.03 to $0.05 per kWh, then the business case for SOLIMS is even more attractive. The cost to continue current operations is over $2.3 Million. However, at a cost of $0.05 per kWh, the cost of owning SOLIMS is expected to be $1.39 Million. Thus, SOLIMS can be operated at 60.3% of the of the alternative. Implementing the SOLIMS alternative provides a savings of over $0.915 Million under the LCC analysis.

Figure 4-4 Annualized Life Cycle Cost Comparison Over 20 Years



In addition, the Annualized Life Cycle Cost (ALCC) of the SOLIMS system was determined. ALCC is beneficial when comparing the LCC of systems on an annualized basis. The ALCC is calculated simply by dividing the LCC by the present worth factor [8]. Under the $0.03 per kWh scenario, the ALCC for SOLIMS is $64,629 where as the ALCC for the alternative is $115,455. In the $0.05 per kWh case, SOLIMS has an ALCC of $97,164 compared to the alternative of $161,175. The results of ALCC for both alternatives can be compared in Figure 4-4 above. Lastly, a simple payback analysis indicates that SOLIMS will pay for itself in 8.49 years when the cost of energy is $0.03 per kWh. When the cost of energy is $0.05 per kWh, the simple payback is 5.1 years.

Chapter 5 - Conclusion

In this report, the opportunity to improve the efficiency of an electric power distribution system was presented. The concept of implementing an intelligent street lighting system called SOLIMS was proposed and further explored. The opportunity for improvement focused on the street lighting system. Data collected from a random sample [23] of photocells is presented to support the idea that an economically feasible opportunity exists to improve energy efficiency and overall management of street lighting systems. Data from the sample photocells indicates that 46 minutes of daily energy usage could be saved. Utility companies should consider implementing smart grid systems such as SOLIMS to improve efficiency in street lighting operations [6] [7] [10] [15] and overall asset management strategies. Energy efficiencies realized will go a long way to counter the eminent retirement of almost 70 GW of fossil-fuel-based generation over the next 3-5 years as forecasted by NERC, the nation's Electric Reliability Organization. Additionally, the rising cost of operating coal and nuclear generating plants, while not a part of the analysis presented, will continue to provide economic incentives for utility companies to modernize street lighting systems. Economic cost pressures on coal and nuclear generation will also force governmental agencies such as state utility commissions, the DOE, the FERC and the EPA to enact regulations that require utility companies to modernize the grid rather than build new fossil-based generation. The international community will also continue to apply pressure to industrialized nations to reduce greenhouse gasses from a global perspective.

The business case presented here strongly supports a utility company modernizing its street lighting operations. The business case also encourages governmental regulators to incentivize utility companies in this area. The LCC [24] analysis presented demonstrates that utility companies have other alternatives to existing practices. SOLIMS is a modern alternative that operates at 55-60% of current practices. Economic incentives are greater as the cost of energy increases, as was demonstrated in the LCC analysis [26]. The uncertainty of future energy prices leads one to conclude that not to modernize the street lighting system is a lost opportunity and may be considered imprudent. Future work on this project includes securing funding to build a more sophisticated test bed to better assess the performance of photocells. A more sophisticated test bed would include advanced metering capability that would record the exact on/off times of the photocell. A prime candidate for advanced metering is the WattNode for MODBUS manufactured by Continental Control Systems, LLC. WattNode for MODBUS is a kilowatt hour (kWh) energy and power meter that communicates on an EIA RS-485 network, measures 1, 2, or 3 phases with voltages of 120-volts AC and alternating current of 5 to 6,000 amps in a wye (phase to neutral) configuration. WattNode for MODBUS is capable of measuring: True RMS Power, Reactive Power, Power Factor, True RMS Energy, Reactive Energy, AC Frequency, RMS Voltage, RMS Current, Demand and Peak Demand. In addition, a communication module needs to be implemented to communicate data from the test bed to a remote server for large-scale analysis of photocell performance. One communications device capable of this task is the eZEio controller, manufactured by eZe Systems, Inc. The eZEio is a basic I/O device with data logging and remote control capabilities. Supporting a wide range of sensor types, the eZEio controller also has a web-base capability that allows remote observations of the lighting system, control of outputs, and the capability to generate and view graphs of logged data. Integrating the WattNode and the eZio into the test bed will allow more accurate data collection and analysis for considering the integration of SOLIMS on a large-scale. Lastly, the communications capability of the eZio will allow further testing of remote control capabilities.

References

[1] R. A. Hargroves, “Road Lighting”, *Physical Science, Measurement and Instrumentation, Management and Education – Reviews,* November, 1983 Vol. 130 Issue 8, pp. 420.

[2] North American Electric Reliability Corporation, “*2010 Special Reliability Assessment: Resource Adequacy Impacts of potential U.S. Environmental Regulations*”, U. S. Federal Energy Regulatory Commission, Docket No. RM-16-000.

[3] Jeff Walters and Lucinda Seigel, (3/2002), “From Engineering to Economics Photocontrol Guide - System Costs Impacted by Photocontrol Choice” for *Engineering to Economics* (Section 2.2) retrieved from http://www.darktolight.com/Resources/PHOTOCONTROLGUIDE/LightingSystemCosts.aspx

[4] IEEE Standard for Broadband Over Power Lines. IEEE Power & Energy Society, (Jan. 7 2009)

[5] Zhen Yu and Zhong Zheng, Analyze the Performance of GPRS DTU and the Impact on the Remote Monitoring. *Global Mobil Cong.,* October 2009, pp 1.

[6] James F. Kurose and Keith W. Ross, *Computer Networking: A Top-Down Approach Featuring the Internet, fifth edition*. Boston, MA: Addison Wesley, 2002, pp 216-227

[7] Robert T. Grow, “Energy Efficient Streetlights, Potentials for Reducing Greater Washington’s Carbon Footprint, American Chamber of Commerce Executives”. Ford Fellowship in Regionalism and Sustainable Development, March 2008.

[8] Roger W. Messenger and Jerry Venture, *Photovoltaic Systems Engineering,* Boca Raton, FL: Taylor and Francis Group, 2010, pp 22.

[9] W. H. T. El-Shirbeeny, M. E. Bakka, Abu Dhabi, in “Experimental Pilot for Automated Street Lighting System in Aby Dhabi Using Powerline Communication, Electronics, Circuits and Systems, 2003”, in *Proceedings of the 2003 10th IEEE International Conf.* vol. 2, pp 743-746.

[10] LiLong ChuXiumin and WuYong WuQing, in “The Development of Road Lighting Intelligent Control System Based on Wireless Network”, in *International Conf. on Electronic Computer Technology,* 2009.

[11] Gustavo W. Denardin, Carlos H. Barriquello, Alexandre Campos and Ricardo N. do Prado, “An Intelligent System for Street Lighting Monitoring and Control”, in *Power Electronics Specialists Conf.*, 2004. Vol. 5 June 2004. IEEE. pp 1 - 5.

[12] J. D. Lee, K.Y. Nam, S.H.Jeong, S.B. Choi, H.S. Ryoo, D.K. Kim, System Development of Zigbee Based Street Light Control, IEEE Power Engineering Society (Oct. 29 2006-Nov. 1 2006) pp 2236 - 2240

[13] Yao-Jung Wen and Alice M. Agogino, “Wireless Networked Lighting Systems for Optimizing Energy Savings and User Satisfaction”, in *Proceedings of Wireless Hive Networks Conf., Austin, Texas, USA*, (August 07-08, 2008).

[14] G. Miguel Ereú and José Omar Mantilla, “A Methodology to Determine Electrical Energy Consumption in Street Lighting Systems”, in *Transmission & Distribution Conf. and Exposition: Latin America, 2006. IEEE/PES*, pp 1-5.

[15] R. Caponetto, G. Dongola, L. Fortuna, N. Riscica and D. Zufacchi , “Power Consumption Reduction in a Remote Controlled Street Lighting System”, in *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, (15-18 Aug. 2006), pp1.

[16] G. Casa, F. Veroni, “A New Way to Manage Public Lighting, Metering and Tariffs for Energy Supply” in *Ninth International Conf. on Technology* (25-28 May 1999), Conference Publication No. 462 IEE 1999, pp 91-95.

[17] Allen J. Wood and Bruce F. Wollenberg, Power Generation Operation and Control. New York, NY: J. Wiley & Sons, 1996.

[18] Turan Goen, *Electric Power Distribution System Engineering*. New York, NY: McGraw- Hill, 1986.

[19] Astronomical Facts, http://www.astronomicalfacts.com/article.html.

[20] National Oceanographic Aeronautical and Atmospheric Administration http://www.srrb.noaa.gov/highlights/sunrise/glossary.html#nauticaltwilight

[21] Peyton Z. Peebles, Jr., Probability, *Random Variables and Random Signal Principles*. New York, NY: McGraw-Hill, 2001.

[22] W. G. Hawley, Line calculations for Major Road-lighting Schemes, *Proceeding of the Institute of Electrical Engineers* (vol. 118, No. 7, July 1971), pp 875-878.

[23] Ward Harrison, Multiple Systems of Distribution Street Lighting, Transactions in American Institute of Electrical Engineers, Volume*: XXXIX* , Issue: 1, (January 9, 1920), pp 33-56.

[24] J.F. Manwell, J.G. McGowan, and A.L. Rogers, *Wind Energy Explained, Theory, Design and Application, 2*nd, West Sussex, UK: John Wiley & Sons 2010.

[25] U.S. Energy Information Agency. (2009). *[Form EIA-861 Final Data File for 2009*]. Retrieved from http://www.eia.doe.gov/cneaf/electricity/page/eia861.html

[26] U.S. Environmental Protection Agency. Retrieved from http://www.epa.gov/osw/nonhaz/industrial/special/fossil/ccr-rule/index.htm

Appendix A - Assumptions and Life Cycle Cost Calculations

Figure A-1 Key Assumptions for Business Case and LCC Analysis

City of Rocky Mount	
Estimated peak load	160 MW
Number of Lamps (250 watt)	2,500
Estimated annual failure rates of photocells @ 9%	225
Estimated Annual kWh (including failures) – Normal	2,286,000
Estimated Annual kWh - Due to failures	486,000
Estimated Annual kWh using SOLIMS	1,626,750
Estimated Energy Cost $/kWh	$0.03 - $0.05
Discount Rate	8%
Inflation Rate	4.0%

The City of Rocky Mount Public Utilities Department (RMPUD - http://ci.rocky-mount.nc.us/utilities/aboutus.html) was used as a case study to conduct the LCC Analysis. RMPUD is a summer peaking utility with peak load of 160 MW and a winter peak of 129 MW [25]. The city serves approximately 30,000 customers. This report estimates that RMPUD has approximately 2500 streetlights in operation. Below are some of the assumptions and sample calculations used to develop the LCC analysis.

Estimated Annual Failure Rates - A failure rate of 9% was used based on research published by American Electric Lighting [15]. An American Electric Lighting survey of electric utilities suggests that the failure rate of photocells is 9.4%. Our LCC analysis used a failure rate of 9%. Thus, for the LCC analysis the number of photocells estimated to fail is determined as follows:

*Est. No. of photocells failed = Total No. of Lamps * 0.09*

*Est. no. of photocells failed = 2500 * 0.09 = 225 failures*

Estimated Annual kWh (including failures) Under Normal Operation: The estimated annual kWh consumed by the street light system including the photocell failures is determined using the calculation below. The kWh savings estimated when using SOLIMS is based on the data recorded from the photocell observations. The sample photocells used to estimate energy savings indicates that when twilight times are used to turn street lights on and off, 46 minutes (converting 46 minutes to hours – [46min/60min]*1hr or 0.77 hours saved) of burn time can be eliminated. Subtracting 0.77 from the 8 hours of normal burn time, we get 7.23 hours. The LCC analysis uses a burn time of 7.23 hours rather than 8 hours. The alternative to continue current operations uses 8 hours and the SOLIMS alternative uses 7.23 hours.

Est. Annual kWh (including failures) = kWh-Normal + kWh-Fail

kWh – normal is the annual kWh consumed by properly working streetlights in current system.

kWh-fail is the additional annual kWh consumed by failed photocells.

kWh-normal = (Total Number of Lamps) * (kW per lamp)*(8 hrs/day)*(30days)*12

kWh-fail = (Total No. of Lamps) * failure rate* (kW per lamp)*(24hrs/day)*30days*12

Thus,

Est. Annual kWh (including failures) = 2500*0.25*8*30*12 + 2500*0.09*0.25*24*30*12

_= 1,800,000 + 486,000.00_

= 2,286,000.00 kWh

Est. Annual kWh using SOLIMS = kWh-Proper with 46 minutes of energy savings from using twilight times.

Est. Annual kWh using SOLIMS = Total No. lamps * kW per lamp*[8 – (46/60)]* 30*12

Est. Annual kWh using SOLIMS = 2500 * 0.25 *7.23 *30 * 12

= 1,626,750 kWh

Table A-1 LCC Results with Energy Cost @ $0.03/kWh

	SOLIMS			Continue Current Operation	
	Capital Cost ($)	**Present Worth ($)**		**Capital Cost ($)**	**Present Worth ($)**
Capital Cost	170,100	170,100		-	-
Energy Cost ($0.03/kwh)	48,803	698,230		54,000	772,592
Maintenance Cost	3,938	56,335		46,875	670,653
Cost of Photocell Failure (24 hour burn time)				14,580	208,600
LCC		**924,665**			**1,651,845**
ALCC		**64,629**			**115,455**

Table A-2 LCC Results with Energy Cost @ $0.05/kWh

	SOLIMS			Continue Current Operation	
	Capital Cost ($)	**Present Worth ($)**		**Capital Cost ($)**	**Present Worth ($)**
Capital Cost	170,100	170,100		-	-
Energy Cost ($0.05/kwh)	81,338	1,163,717		90,000	1,287,653
Maintenance Cost	3,938	56,335		46,875	670,653
Cost of Photocell Failure (24 hour burn time)				24,300	347,666
LCC		**1,390,151**			**2,305,972**
ALCC		**97,164**			**161,175**

Each SOLIMS is estimated to cost $2700 per unit and each unit is expected to control 40 streetlights. Thus, the capital cost was determined as follows:

No. Of SOLIMS Units Required = Total No. of Street lights / 40
_= 2500/40_
= 62.5 (approximately 63 units of SOLIMS)
Capital Cost = No. of SOLIMS * $2700 = 63 * $2700
_= $170,100_
Present Worth Factor = [(1-x^n) / (1 – x)]

(NOTE_: The formula's used to determine present worth factor and present worth were taken from:_ Roger W. Messenger and Jerry Ventre, Photovoltaic Systems Engineering, Boca Raton, FL: Taylor and Francis Group, 2010, pp 335)

and, x = [(1+i) / (1+d)]
Where,
i = inflation rate
d = discount rate
n = 20 years
_x = [(1+i)/(1+d)]_
_x = (1+0.04) / (1+0.08) = 1.04 / 1.08 = 0.96296296_
Present Worth Factor (Pa) = [(1-x^n)/(1-x)]
Present Worth Factor (Pa) = [(1- 0.96296296^20) / (1-0.96296296)]
_= 14.30725835_

LCC Calculations – Energy Cost @ $0.03/kWh

SOLIMS – LCC Calculations

Energy Cost ($0.03/kWh) = Est. Annual kWh * $0.03 kWh
= 2500*0.25*7.23*30*0.03*12 [**note:** 7.23=8hrs -(46min/60min)*1hour]
_= $ 48,803_
PW (energy cost @ $0.03/kWh) = Present Worth Factor *($48,802)=14.30726*($48,803)
= $ 698,230
PW (maintenance cost) = Present Worth Factor *(annual maint. cost)

*[**Note:** 25% of all units require maint. annually at a cost of $250 each - i.e. annual maint. cost = 0.25*63*250=$3,938]*

= 14.30726($3,938)*
= $ 56,335
LCC($0.03/kWh) = Capital Cost + PW(energy cost) + PW(maint. cost)
= $170,100 + $698,230 + $56,335
= $ 924,665
Annualized LCC = PW/PWfactor
=$924,665 / 14.30726
= $64,629

<u>Continue Current Operations ($0.03/kWh) – LCC Calculations</u>
*Energy Cost ($0.03/kWh) = Est. Annual kWh * $0.03 kWh*
*= 2500*0.25*8*30*0.03*12*
= $ 54,000
Cost of Photocell Failure = Tot. No. Lights(9%failure rate*kW*(24hrs)*(30days)*12months*($0.03/kWh)*
*= 2500*0.09*0.25*24*30*0.03*12*
= $14,580

*Maintenance Cost = 15% *Tot. No. lights*(125) [Note: 15% of all lights will require maintenance at a cost of $125 each)*
*= 0.15*2500*$125*
= $46,875
Present Worth Factor = 14.30726 (same as above)
PW (energy cost @ $0.03/kWh) = 14.30726($54,00)*
= $772,592
*PW (maintenance cost) = 14.30726 *($46,875)*
= $670,653
PW(photocell failure) = PW*$14,580 = 14.30726*$14,580
= $ 208,600
LCC($0.03/kWh) = Capital Costs + PW(energy cost) + PW(maint. cost) + PW(failure costs)
= 0 + $772,592 + $670,653 + 347,666
= $1,790,911
Annualized LCC = PW / PWfactor
=$1,790,911 / 14.30726
= $125,174

LCC Calculations – Energy Cost @ $0.05/kWh

<u>SOLIMS – LCC Calculations</u>
*Energy Cost ($0.05/kWh) = Est. Annual kWh * $0.05 kWh*
*= 2500*0.25*7.23*30*0.05*12*
= $ 81,338
*PW (energy cost @ $0.05/kWh) = Present Worth Factor *($81,338)=14.30726*($81,338)*
= $1,163,716

*PW (maintenance cost) = Present Worth Factor *(maint. cost)*
= 14.30726($3,938)*
= $ 56,335
LCC($0.05/kWh) = Capital Cost + PW(energy cost) + PW(maint. cost)
= 170,100 $1,163,717 + $56,335

= $1,390,152
Annualized LCC = PW / PWfactor
=$1,390,152 / 14.30726
= $97,164

<u>Continue Current Operations ($0.05/kWh) – LCC Calculations</u>

*Energy Cost ($0.05/kWh) = Est. Annual kWh * $0.05 kWh*
*= 2500*0.25*8*30*0.05*12*
= $ 90,000
Cost of Photocell Failure = Tot. No. Lights(9%failure rate*kw*(24hrs)*(30days)*12mnth*($0.03/kWh)*
*= 2500*0.09*0.25*24*30*0.05*12*
= $24,300
Present Worth Factor = 14.30726 (same as above)
PW (energy cost @ $0.03/kWh) = 14.307($90,000)*
= $1,287,653
*PW (maintenance cost) = 14.30726 *($46,875)*
= $670,653
PW(photocell failure) = PW*$24,300 = 14.30726*$24,300
= $ 347,666
LCC($0.03/kWh) = Capital Cost + PW(energy cost) + PW(maint. cost) + PW(failure costs)
= 0 + $1,287,653 + $670,653 + 347,666
= $2,305,972
Annualized LCC = PW/PWfactor
=$2,305,972 / 14.30726
= $161,175

Maintenance Cost Assumptions (SOLIMS) - The assumption was made that 25% or 15.75 of the SOLIMS units would require maintenance on an annual basis. This maintenance is includes scheduled inspection and testing by trained line crew personnel to insure operation of the installed system. The cost of maintenance is estimated to be $250 per unit inspected on an annual basis.

Maintenance Cost Assumptions (Continue Current Operations) – Maintenance cost to continue current operations includes the estimated value that 15% of all 2500 street lights will require maintenance related to the photocell.