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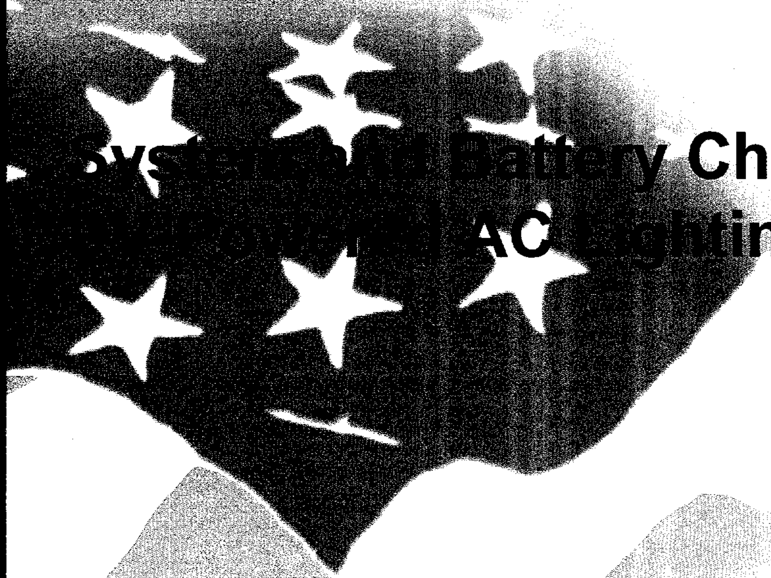

System and Battery Charge Control for PV-Powered AC Lighting Systems

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System and Battery Charge Control for PV-powered AC Lighting Systems

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Abstract

This report reviews a number of issues specific to stand-alone AC lighting systems. A review of AC lighting technology is presented, which discusses the advantages and disadvantages of various lamps. The best lamps for small lighting systems are compact fluorescent. The best lamps for intermediate-size systems are high- or low-pressure sodium. Specifications for battery charging and load control are provided with the goal of achieving lamp lifetimes on the order of 16,000 to 24,000 hours and battery lifetimes of 4 to 5 years. A rough estimate of the potential domestic and global markets for stand-alone AC lighting systems is presented. DC current injection tests were performed on high-pressure sodium lamps and the test results are presented. Finally, a prototype system was designed and a prototype system controller (with battery charger and DC/AC inverter) was developed and built.

The work described in this report was performed for Sandia National Laboratories under Contract No. BD-0005B.

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Acknowledgments

The author would like to thank the Energy Storage Systems Program at Sandia National Laboratories and the Department of Energy's Office of Power Technologies for sponsoring this work.

Patent Pending

On November 20th, 1998, a patent application was filed with the United States Patent and Trademark Office. Some of the features detailed in the patent are described in this report. Therefore, public disclosure of this report is allowed after November 20th, 1998. Below is the abstract of the patent application.

> *A system for delivering power to a battery and to a load includes a power source that supplies energy to the battery and the load. The battery can be charged by the power source and used to supply energy or power to the load when the power source is unable to provide sufficient energy and power to the load. The system reduces injection of DC current into the load and, as a result, extends the operation life of the load, particularly if the load is an AC lighting or lamp system. The system operates the load in an optimal manner such that battery storage is maintained at near full charge, yet the lighting load operates for a maximum number of hours per night. The benefit of the system is to prevent early failure of either the lighting load or the battery.*

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Acronyms and Abbreviations

AC	alternating current
CF	compact fluorescent
CRI	color rendering index
CVLC	constant-voltage limited-current
DC	direct current
F	fluorescent
HAL	halogen
HALT	highly-accelerated lifetime testing
HID	high-intensity discharge
HPS	high-pressure sodium
I	incandescent
K	kelvin
LED	light emitting diode
LPS	low-pressure sodium
LVD	low-voltage disconnect
L/W	lumens per watt
MH	metal halide
MPT	maximum power tracking
MTBF	mean time between failure
MV	mercury vapor
PV	photovoltaics
PWM	pulse width modulated

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Executive Summary

This report reviews a number of issues specific to stand-alone AC lighting systems. Photovoltaics (PV) can be the power source for such systems. It is also possible to power such lighting systems using small wind turbines. A review of AC lighting technology is presented. The pros and cons of various lamps are discussed, the best of which are compact-fluorescent for small lighting systems and high-pressure sodium or low-pressure sodium for intermediate-size systems.

Specifications for both the PV and wind generated battery charging and load controls are presented. Some of the specifications are directed towards achieving the maximum battery and light fixture lifetimes. Lamp lifetimes on the order of 16,000 to 24,000 hours should be achievable, which corresponds to 5 to 10 years between lamp replacements. It is also a goal to achieve battery lifetimes up to 4 to 5 years, in line with manufacturer specifications.

The application requirements of intermediate-size (35 to 100 W) lighting systems are presented. Some estimates of market potential are made, with the world market predicted to be as large as $2 billion per year, but it is understood that there may be significant errors in the market estimates.

Test results of DC current injected into 70-W high-pressure sodium lamp fixtures are presented. Further testing is needed to reach broad conclusions, but our estimate is that if the DC/AC inverter injects less than a 0.56% DC to AC voltage ratio into this fixture, we should expect to achieve operation to 16,000 hours.

Finally, a prototype system controller with a battery charger and DC/AC inverter has been built. Ascension Technology intends to continue developing this controller specifically for use in intermediate-size stand-alone AC lighting systems.

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1. Application Requirements

The Application Defined

The application that is targeted for this study is for intermediate-size (35- to 100-W) AC area lighting systems that are powered from a renewable resource such as photovoltaics (PV) or a small wind turbine. Because the power source and lighting loads are not coincident, some form of energy storage is required, in this case battery storage.

These systems are typically stand-alone; they are not connected to any other source of power. Such systems are needed in remote locations where getting a source of power can be an expensive proposition. Such sites exist both in developed and undeveloped countries for outdoor area lighting. In the United States, electric utilities are often expected or asked to provide area lighting.

Area lighting may be used to light a dark crossroads out in the country, or to provide lighting at a boat ramp so that at the end of the day, boaters can safely see to pull their boat out of a lake. Rural farmers and landowners use area lighting to help deter theft or vandalism. A typical light used at many rural locations is a 70-W high-pressure sodium lamp. Area lighting systems may be used to light the streets in villages or a town square for small villages without access to power.

Area lighting systems can also be used to supplement security lighting systems, such as fence perimeters. These systems each have their own power supply and battery backup and can operate without the main power source. Area lighting provides orientation and direction finding capability in the dark but is not always sufficient for specific task work.

Area lighting is distinct from street lighting requirements, particularly in the U.S. Street lights in the U.S. typically start at 100 W and get larger. A common street light size in a residential neighborhood in Colorado is 100 or 250 W. Traffic lighting and railroad crossing power requirements in the U.S. are large compared to area lighting systems, with power requirements in the hundreds of watts to kilowatts. Billboard lighting systems are also considered large lighting systems.

Standard billboards across the United States use 400-W Halophane light fixtures. A normal billboard uses from two to eight such fixtures, for a total load of 800 to 3200 W. The amount of billboard lighting needed depends upon the amount of ambient light in the area. Because one of the purposes of a billboard is to catch a viewer's attention, it needs to be brighter than ambient. Because of these reasons, the best locations for PV-powered billboards tend to be remote locations, where AC power is not available and ambient lighting is low or non-existent.

PV has not sufficiently penetrated these large-load markets because the cost of PV to power such large loads is considered prohibitively high. The cost of PV lighting systems is directly related to the power rating and energy consumption of the lighting loads.

On the other end of the spectrum, hardware is readily available for small PV lighting systems. Systems as small as a few watts are used for pathway lighting and can be found in hardware stores. Most distributors of PV lighting equipment sell lights with integral DC ballasts for these lower-power applications. However, these small lighting systems often do not produce enough light to provide outdoor area lighting for all applications.

For the purpose of defining system size, systems with lighting loads less than 35 W are considered small systems, and can typically be powered by off-the-shelf DC equipment. Systems with lighting loads greater than 100 W are considered large lighting systems. Reliable, rugged equipment is not readily available for intermediate-sized lighting systems (35 to 100 W).

Summary of Lamp Technologies

Table 1 lists the lamp technologies that were investigated in the 35- to 100-W power range. Some lamps above and below that range were also investigated.

The color rendering index (CRI) is a measure of the ability of a light source to represent colors in objects. It is a scale from 0 to 100. A CRI of 100 has the rendering capabilities of incandescent light (for sources below 5000°K) or "daylight" for sources above 5000°K). The most common measure of lamp efficiency is lumens per watt (L/W). Lumens is a measure of the light output of the lamp.

Table 1. Summary of Lamp Technologies [22]

Technology	CRI	Efficiency (L/W)	Lifetime (hours)	Power Rating (W)
Incandescent	100	4 to 25	75 to 8760	3 to 1500
Halogen	100	10 to 25	1,000 to 4000	15 to 750
Compact Fluorescent	75 to 82	48 to 86	7000 to 20,000	5 to 50
Fluorescent	51 to 95	34 to 104	6000 to 24,000	4 to 215
Mercury Vapor	20 to 50	18 to 63	12,000 to 24,000	50 to 1000
Metal Halide	65 to 85	59 to 125	3000 to 20,000	39 to 1800
Low-pressure Sodium	0	100 to 183	14,000 to 18,000	18 to 180
High-pressure Sodium	20 to 85	35 to 150	10,000 to 24,000	35 to 1000

Incandescent

Incandescent (I) lamps (see Figure 1) are common for indoor household use and are rather inexpensive. It is well known that incandescent lamps are not very efficient. Incandescent lamps turn on instantly when power is applied. Incandescent lamps provide a "warm" color rendition. As an example, a series of lamps used for street lighting applications was found [23]. In this series, the lamps ranged from 92 to 448 W at 120/125 V. The initial lamp output ranged from 1000 to 6000 L. The lamp efficiency ranged from 9.5 to 14.8 L/W. The rated lamp lifetimes were 3000, 6000, and 12,000 hours.

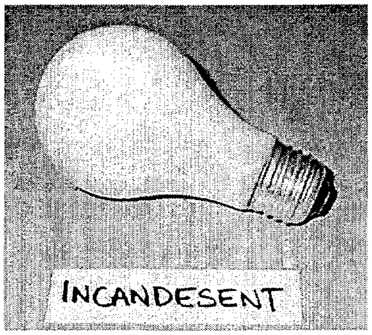

Figure 1. Incandescent lamp.

Lamps with longer lifetimes had lower efficiency. The lamps with higher power output had higher efficiency. An example is a GE 105A23/12/125V lamp, rated for 125 V, 1000 L, 105 W, 9.5 L/W, 12,000 hour lifetime, A-23 style lamp.

Halogen

Halogen (HAL) lamps (see Figure 2) are also common in household and outdoor lighting applications. They are somewhat more expensive and not very good in efficiency. Halogen lamps provide a white-light color rendition, but in most other respects are similar to incandescent lamps.

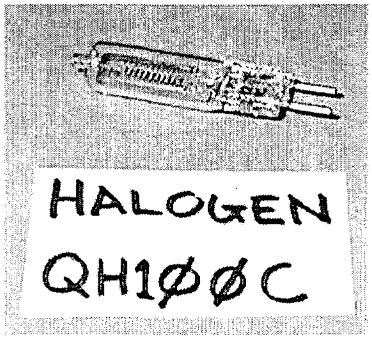

Figure 2. Halogen lamp.

Compact Fluorescent

Compact fluorescent (CF) lamps are only available in small sizes. These units require a ballast to drive the lamp from the power source. The ballast is found either in the lamp base for socket mounting or may be separate. CF lamps found in hardware stores typically come with AC ballasts. DC ballasts may be obtained from specialized PV supply distributors.

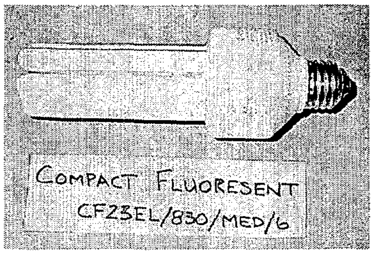

Figure 3. Compact fluorescent lamp.

Fluorescent

Other fluorescent lamps are also available, and perform similarly to CF lamps. Fluorescent lamps require a ballast sized for each lamp type or combination of lamps.

Mercury Vapor

"Mercury vapor [MV] lamps, with their blue-green color and long life, are the preferred source for landscape and sign lighting, and are also used in a broad range of street lighting and industrial applications. Featuring very long lifetimes of over 24,000 hours, mercury vapor lamps have a CRI of up to 45 and efficacies ranging from 32 to 63 lumens per watt." [22] MV lamps require a ballast sized for each lamp size.

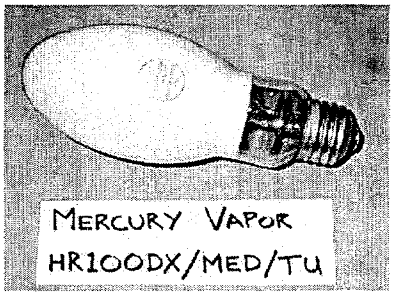

Figure 4. Mercury vapor lamp.

Metal Halide

"Metal halide [(MH)] lamps, best known for the cool white light that so dramatically highlights architecture, bridges and monuments, are also used in sports and street lighting, and indoors in industrial, commercial and retail applications. They have the best overall color rendering properties (2-92 CRI) among HID [high-intensity discharge] lamps, and now MasterColor™ metal halide, Philips' most recent technological advancement, offer impressive color consistency improvements as well. In addition, Metal Halide lamps provide high efficacies of 80 to 125 lumens per watt and life expectancies of 4500 to 20,000 hours." [22] MH lamps are one of several types of HID lamps. MH lamps also require a ballast sized specifically for each lamp type.

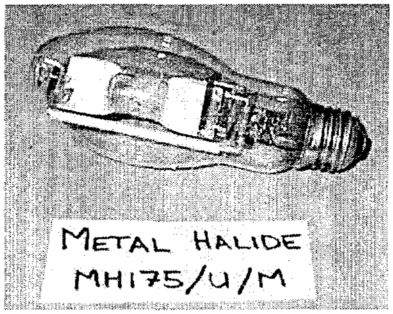

Figure 5. Metal halide lamp.

Low-pressure Sodium

Low-pressure sodium (LPS) lamps are the most efficient lighting source available when measured in L/W. LPS lamps generate a monochromatic yellow light that does not give very good color rendition, and which is considered objectionable by some people. LPS lamps have a CRI of 0. Two typical lamp sizes are 18 W and 35 W, rated at 1800 and 4800 L, respectively. LPS lamps are *not* HID lamps.

High-pressure Sodium

High-pressure sodium (HPS) lamps (see Figure 6) are a form of HID lamp. Ballasts for HPS lamps must include a starting circuit that generates a high-voltage pulse to ignite the arc in the lamp. When the lamp is operating, it presents a low impedance to the ballast, and the lamp operates at 52, 55, or 100 V nominal, depending upon its rating.

"High pressure sodium lamps offer average life expectancies of 24,000 hours and outstanding efficacies of 40 to 140 lumens per watt. Originally associated with a poor CRI of 22, HPS lamps now have color rendering indices as high as 85 and include lamps with features designed for enhanced energy savings, visual comfort and instant restrike in street, outdoor, industrial, security, retail and office lighting applications." [22]

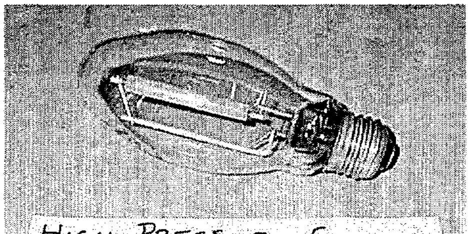

Figure 6. High-pressure sodium lamp.

General Electric (GE) provides HPS lamps in the 35- to 1000-W range.[10] End of life is defined as a reduction in light output by a factor of 0.73. Figure 7 shows HPS lamp lifetime as a function of how many hours per start cycle the lamp is operated. If the lamp is turned on once per day and operates for 5 hours, then the lamp should last nearly 10 years before needing replacement.

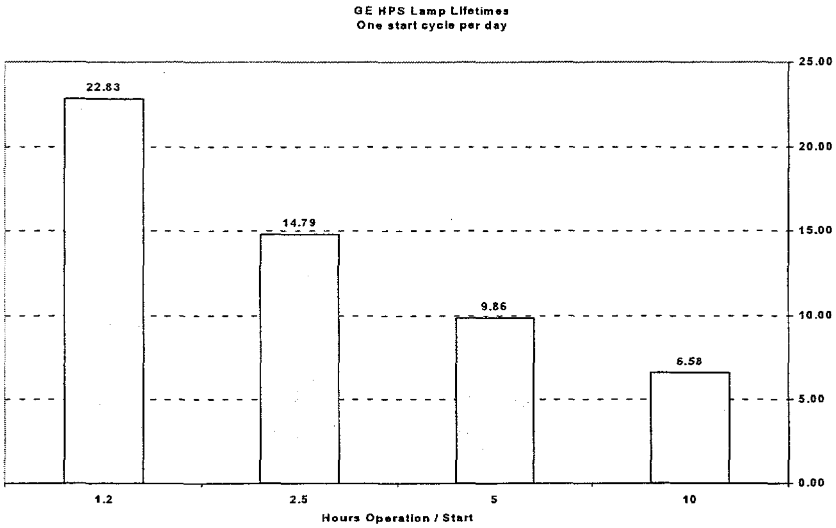

Figure 7. GE HPS lamp lifetimes.

Figure 8 shows the efficiency of the GE HPS lamps. As is typical with other lighting technologies, lamps with higher power ratings are more efficient at generating light. It is this very high efficiency that has led to the widespread use of HPS lamps for street lighting applications.

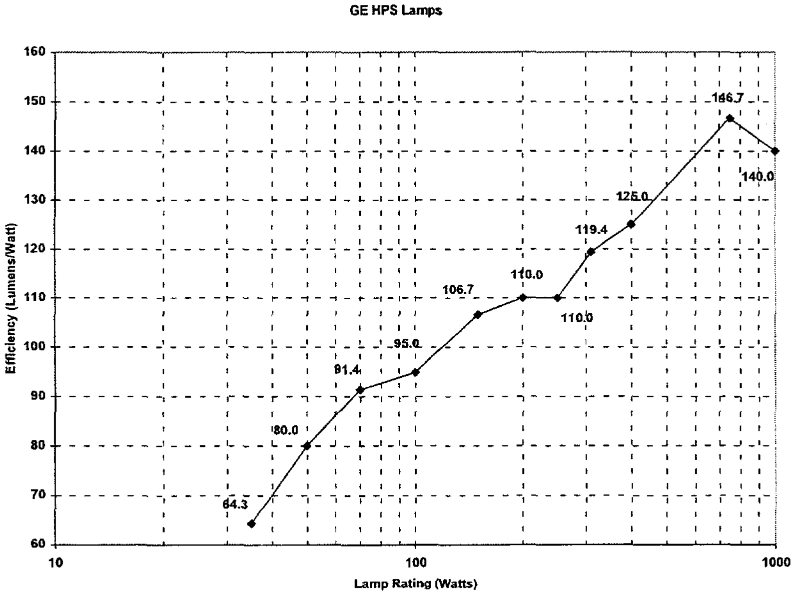

Figure 8. GE HPS lamp efficiencies.

A Simple Life-cycle Cost Analysis of Lamp Technologies

The initial capital costs and average annual maintenance costs are computed for an area lighting system using various lamp technologies. A simple test case is posed and costs are computed. Thirty-eight lamp characteristics were found representing the different lighting technologies. The lamp characteristics included initial lumens, power rating, approximate retail price, and average lamp lifetime in hours. The system requirements and assumptions on system operation are shown in Table 2.

Table 2. AC PV Lighting System Life-cycle Cost Assumptions

Cost of PV	\$4/W
Cost of batteries (12-V)	\$1/Ah
Hours of operation per night	8
Light requirement	5000 L
Battery storage efficiency	80%
System controller efficiency	95%
Ballast efficiency (when used)	90%
Days of storage autonomy	4 days 100% DOD
Battery replacement cycle	5 years
Lamp replacement at end of life	varies
Labor cost and expense per site visit:	
Case A	\$50/visit
Case B	\$500/visit
PV resource, sunhours per day	5
System operates the same in winter and summer.	-

Case A is the case where labor for site visits is relatively low. This would be the case when the system is close to service personnel or labor rates in the region are low. Case B is the case where labor and expenses to visit the site are higher, such as might be the case for U.S. utility workers visiting a remote location. The labor rate is the only parameter varied among cases A and B. Case B reflects the higher cost to service the site periodically, and is especially expensive for lighting technologies that have a short lamp lifetime.

Figure 9 shows the total life-cycle cost of the major system components, PV, batteries and lamps, and labor and expense to service the site for lamp replacements or battery replacements for Case A. Not all system costs are included because the goal is to compare various lamp technologies. The data is normalized on a dollar per lumen basis so that technologies with large differences in power (and light) ratings can be compared.

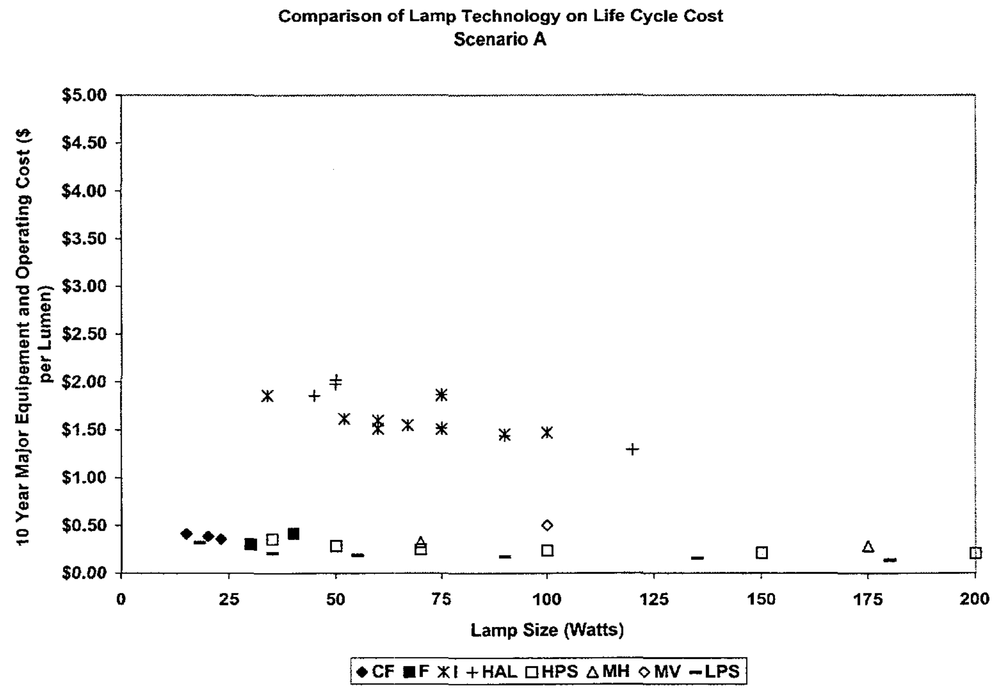

Figure 9. Case A comparison of lamp technologies' life-cycle costs.

Figure 10 shows the data for the Case B computation, with high labor rates for site visits. In some cases the costs are much higher due to lamps with shorter lifetimes requiring more frequent site visits.

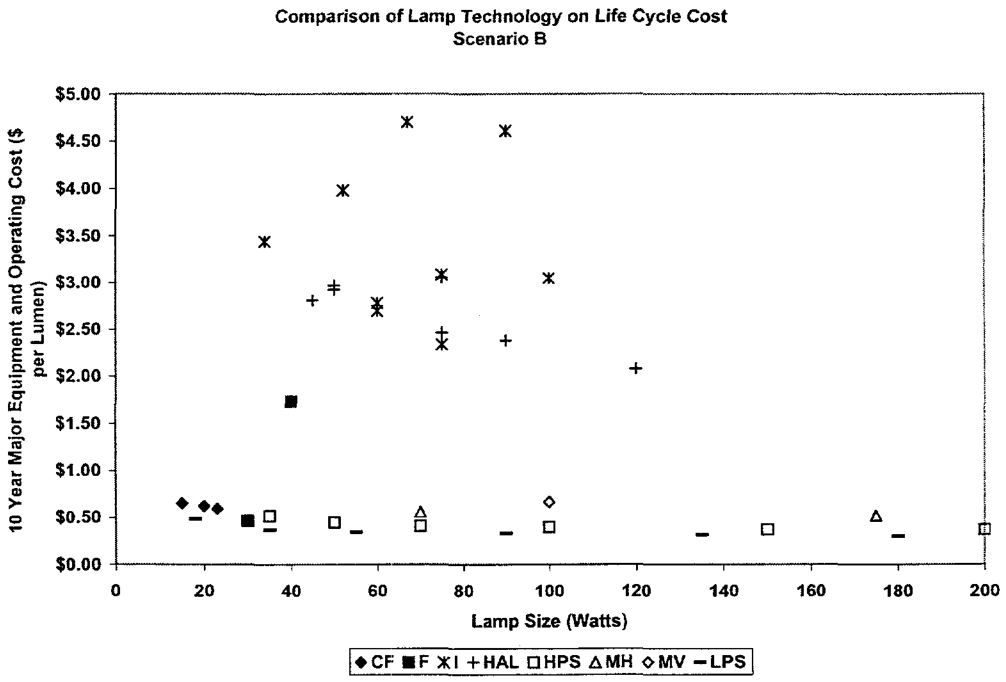

Figure 10. Case B comparison of lamp technologies' life-cycle costs.

Two main groupings are obvious in the data. The high-cost lighting methods are incandescent (I) and halogen (HAL) lighting. The lower cost methods are compact fluorescent (CF), fluorescent (F), high-pressure sodium (HPS), metal halide (MH), mercury vapor (MV), and low-pressure sodium (LPS). These lower-cost lighting methods are shown in more detail in Figure 11.

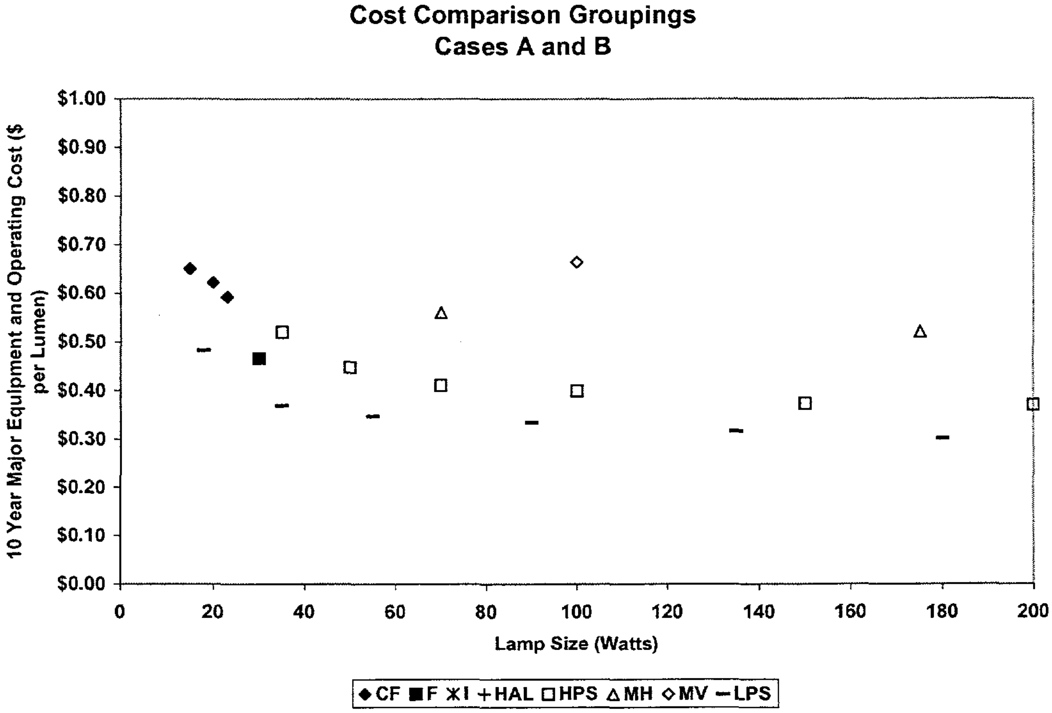

Figure 11. Cost comparison groupings for Cases A and B.

As can be seen in this figure, low-pressure sodium appears as the most cost-effective means in a PV-powered AC lighting system. LPS does have a major drawback not reflected in the figure; it is considered to have objectionable color rendition properties by some people. Therefore, this should be considered when choosing it as an option for area lighting. The second most cost effective method is high-pressure sodium. Although it has similar color rendition characteristics as low-pressure sodium, they are not as strong, and therefore not as objectionable. High-pressure sodium is the most common standard for street lighting applications in the U.S.

Use of compact fluorescent lighting is cost effective when the system size is small. Metal halide and mercury vapor lighting are also reasonably cost effective and may be used when color rendering is more important.

Each of these lighting technologies has pros and cons. All of these lighting technologies are available in standard products for outdoor lighting when powered from AC power. Some applications are best served with high-pressure sodium, others with low-pressure sodium, and still others with compact fluorescent lights.

System Specifications

A PV-powered AC lighting system should have the following features:

- Capable of utilizing any AC lighting technology, ultimately giving the customer the greatest choice in quality of lighting.
- Designed and produced well enough to achieve the limits of technology in terms of performance and reliability. Systems that are not properly designed and tested prior to market introduction do not serve the industry's long term interests. Once a system is properly installed and operational, system failures should be limited to lamps reaching full end of life and maintenance and replacement of batteries at their design lifetime.
- An indication of the expected lamp and battery replacement cycle and procedures. A maintenance log provided with each system would help the operator to keep track of when battery and lamp replacement is due.
- Good aesthetics—aesthetics of the system are important to some customers. In these cases it is important to provide a well-integrated system.

System Design Day and System Sizing

Most locations have different solar resources from winter to summer months. System sizing and orientation depend upon the energy usage required of the load at different times of year. In North America, systems that have constant load requirements throughout the year will typically have a system "design day" in a winter month.

A system designed for use at a recreational area that is only open from spring to fall may have a design day in April or October. Such a system, which is not required to operate in the winter, still needs to maintain battery health during that time even if the load is switched off.

- If the system will have loads that are switched off or not operating for long periods of time, then the charge controller part of the system should include float voltage operation to prevent excessive overcharging of the batteries. A three-stage (bulk, regulation, and float) charge controller will accomplish that. [20]
- If the system is expected to operate continuously throughout the year, then a two-stage (bulk and regulation) battery charger may be acceptable.
- If the system will have periods of time when the PV (or wind) resource will be insufficient to operate the load for a fixed number of hours per night, then the load control part of the system should be capable of "automatic load operation." In automatic operation, the load's hours of operation are reduced automatically to prevent excessive deep discharge of the batteries.

Battery Charging Requirements

The requirements below apply to the charging of batteries from PV for standalone applications. These requirements may or may not apply to other applications.

Bulk Charging

Bulk charging is the first phase of charging a battery, where the battery voltage is lower than the regulation voltage set point. Typically, the maximum power available from the PV is less than the maximum amount of power the battery can accept, so maximum power tracking (MPT) is possible during this phase of charging. If the PV and battery are well matched with respect to the maximum power point voltage during charging, then a maximum power point controller provides minimal added benefit. The temperature coefficients of both the battery and PV should be accounted for to ensure the best match for the specific conditions of the system's design day. Other benefits of MPT are as follows:

- MPT of the input power source allows less exact matching of the power source voltage characteristics to the battery characteristics.
- MPT can reduce the power source's size requirement due to gains in bulk charging efficiency for the design day.

Regulation Voltage Charging

During regulation voltage charging, as long as power is available from the power source, battery voltage is held at a fixed regulation voltage set point. The voltage regulation set point should be temperature compensated based on battery temperature and chemistry, otherwise, over or undercharging of the battery will occur resulting in shorter battery lifetime. When selecting a charge controller, the following items should be considered:

- On/off charge controllers achieve voltage regulation by using two set points, disconnect and reconnect.
- Constant voltage pulse width modulated (PWM) charge controllers are typically on/off charge controllers that operate at a higher frequency, usually 100 to 500 Hz. The battery voltage averages to the regulation voltage set point.
- Both on/off and constant-voltage PWM charge controllers run the risk of damaging batteries and load-connected equipment if the battery bank develops a high resistance condition, as might occur in some lower quality batteries at end of life. This condition may also occur if the charge controller continues to try to charge the batteries when they have been disconnected and the controller keeps the load connected. Open-circuit voltage of the power source must be prevented from being connected directly to the load in this fault condition, otherwise damage to the load may occur due to the higher-than-normal voltage.

Float Voltage Charging

Three-stage charge controllers include float voltage operation. This is the same mode of operation as regulation voltage operation, except that the set point is lower. This prevents a fully charged battery from excessive overcharging.

> *"Proper float voltage minimizes positive grid corrosion. Long term floating of a battery either below the recommended float range (undercharging) or over the recommended float range (overcharging) [discharges the battery or] increases the positive grid corrosion and decreases life."[16]*

When selecting the proper set point, it is important to remember:

- The float voltage set point depends upon battery chemistry.
- The float voltage set point must also be temperature compensated as per manufacturer's recommendations.

Constant-voltage Limited-current Charging

Constant-voltage limited-current (CVLC) charging provides the greatest control over the battery charging process. CVLC charging is similar to constant-voltage PWM charging, but with the added ability to control the charging current from zero to the maximum available charging current. This control is achieved by filtering the PWM output with an inductor and a capacitor, which creates a true DC/DC converter in the process. Feedback of the output current is used to control charging current into the battery.

High-power Input

The battery charge controller must be able to handle over-irradiance conditions, or the system must be designed such that those conditions will never occur. Anecdotal stories of charge controllers that fail during operation in cold conditions with high (> 1100 W/m^2) irradiance occur. Either enough design margin must be included in the charger design, or a means to prevent excessive battery charge current should be included.

Temperature Compensation

Adjustment of the regulation and float voltage set points must be included to prevent over or undercharging the battery. The slope of temperature compensation depends upon battery chemistry (see Table 3).

Battery Technology Selection

The two most common battery technologies in use today in standalone PV systems are flooded lead-acid and sealed gel-type batteries. These two technologies have different charging set points, as shown in Table 3.

Table 3. Example Battery Charging and Load Control Set Points for 12-V Batteries at 25°C

	Equalization Voltage (V)	Regulation Voltage (V)	Float Voltage (V)	Low-voltage Disconnect (V)	Low-voltage Reconnect (V)	Temperature Compensation (mV/°C)
Flooded lead-acid	15.3	14.4 to 14.7	13.65 or Man. Spec	11.5 to 11.88	>13.0	-30
Sealed gel	14.1 or 14.4	14.1 or 14.4	Man. Spec	11.46 to 11.88	>13.0	-30 or Man. Spec.

Load Control Requirements

The requirements below apply specifically to PV/battery-powered AC lighting equipment. These requirements may or may not apply to other applications.

Low-voltage Disconnect

In solar home systems, users will often connect loads directly to the battery rather than to the system controller. Or they will short out, or shunt, the load control feature. They do this to disable the low-voltage disconnect (LVD) of the controller. Obviously, this causes the battery to be discharged far more than should be allowed, and will cause the battery to fail sooner than would normally occur. One researcher has suggested that controllers be able to provide an LVD warning, rather than an actual disconnect, and let the user decide if they will turn off the loads themselves. Therefore, three possibilities are available for LVD provisions.

- No low-voltage disconnect
- Low-voltage warning light (as used in automobiles)
- Low-voltage disconnect with display

Soft Start

Each time a lamp is started, its lifetime decreases from the starting operation. Soft start is a feature commonly applied to lighting technologies other than HID lighting. It can be found in DC ballasts for compact fluorescent lamps. Unitrode has a control chip [27] that incorporates soft start in a single-chip, DC-ballast design for cold-cathode fluorescent, neon, and other gas discharge lamps.

Open Lamp Detect and Shutdown

Some ballasts undergo excessive component stresses when attempting to light a lamp that is failed open or when no lamp is in the fixture. These ballasts should have an open lamp detect circuit that prevents the unit from attempting to light a lamp for an indefinite amount of time. The stresses that ballasts undergo are very specific to the ballast design. Open lamp detection is not required in all ballast designs. Ballast designers should be aware of this effect and provide open lamp detection and shutdown to protect the ballast from excessive component stress to extend ballast lifetime as long as possible.

Automatic Load Control

See the section “Battery Charging Requirements,” above.

Standards

UL 1741 – *Proposed First Edition of the Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems.* Although not commonly known or applied, Underwriter’s Laboratories, Inc. does have a standard that applies to PV battery charge controllers and inverters used in PV systems. UL is primarily concerned with product safety and fire prevention and generally does not address performance, mean time between failure (MTBF), or product reliability.

2. Definition of User Needs

Gaps in Existing Technology

The major components in self-powered AC lighting systems are listed below. In each case, a determination is made as to whether or not a gap in technology exists that is limiting implementation of these AC lighting systems.

Renewable Power Sources

PV and or small wind turbines may be used to power self-powered AC lighting systems. If there is any gap at all in this area, it would be the relatively high cost of PV and wind compared to other means of providing power. This gap tends to limit the size of lighting systems to small systems only. It is not the intent of this project to directly address this issue. The cost of PV and wind power sources continues to decline, in good part due to the support of the U.S. Department of Energy. As the costs of PV and wind generation decline, the cost-effective size of AC lighting systems will increase. With present pricing of PV and wind, there is a sufficient market for small- and intermediate-size AC lighting systems.

Batteries

Batteries are a very mature technology, but also are improving with time. Although battery failures are a problem to be avoided in stand-alone systems, it is generally not the fault of the battery hardware. Sources of suitable quality batteries do not appear to be a limiting factor when implementing self-powered AC lighting systems.

Lighting Hardware

AC-powered lighting hardware is commonly available. It comes in a wide variety of sizes, ratings, shapes, colors, technologies, and prices. It is available for service in industrial, commercial, or residential locations. Architectural poles and fixtures are used where appearance is important. AC lighting is manufactured in huge volumes relative to the size of the PV industry, and constitutes a significant portion of the total energy consumption in the U.S. It does not appear that there are any limiting factors in AC lighting hardware when implementing self-powered AC lighting systems.

AC Lighting System Controls

AC lighting system controls must provide battery charging control and properly regulated power to the load. Although one could build a self-powered AC lighting system with off-the-shelf components today, such a system would have the following drawbacks:

- Low level of integration of the battery charger and inverter components for loads sized from 35 to 100 W.
- Low quality of inverters, leading to potential reliability problems. One inverter found in a computer supply store, designed to operate from a 12-V battery, was found to have paper insulation between the power circuits and chassis. This inverter cost about $60 and could power up to 140 W continuous, but clearly it would not survive long-term operation in a stand-alone AC lighting system.

In summary, it appears that the main components that prevent large-scale implementation of stand-alone AC lighting systems are the system controller, charger, and inverter.

Proposed System Design

Design of the system controller must be made in the context of the system in which it will be used. There are indeed many variations to how stand-alone AC lighting systems may be designed. Figure 12 is a drawing of the major components in such a system.

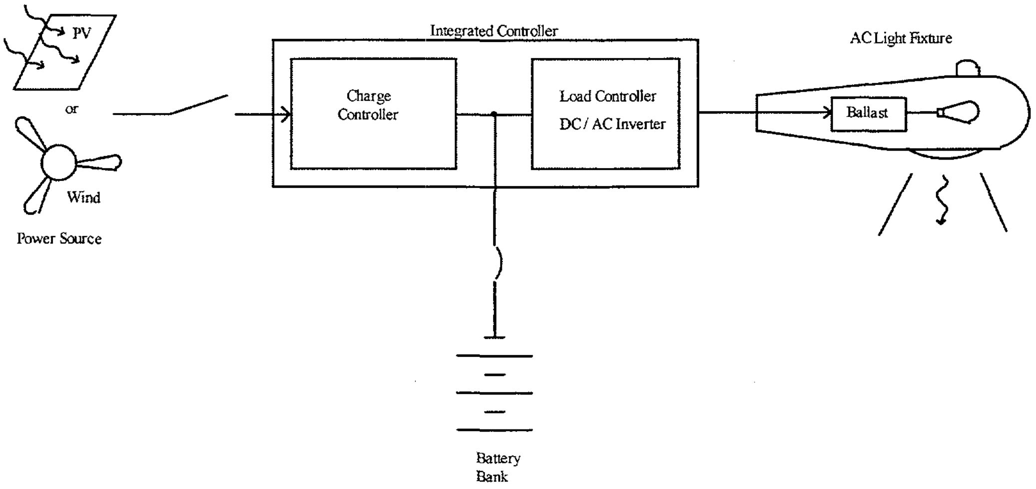

Figure 12. Proposed system design.

Features of the Charge Controller

- MPT of the power source is possible during bulk charging.
- CVLC, DC/DC charge controller.
- Three-stage charge control: bulk, regulation, and float.
- Limited-current charge control allows best possible charging without generating overvoltage conditions on the battery, even if battery resistance increases at end of battery life.
- Factory calibrated with standard, fixed, voltage regulation set points. User may adjust the set points for use with different battery chemistries by following the provided procedure.
- Light emitting diode (LED) indication of charging function.

Features of the Load Controller

- LED indications of LVD.
- Factory-calibrated LVD.
- Selection switch for setting hours of operation of the lighting load, including off, on 24 hours, and split evening/dawn operation.
- Automatic/fixed hours of operation selection switch. In the automatic setting, the unit will modify the battery's selected hours of operation depending upon the battery's state of charge and the availability of power resources to prevent the battery from operating in a continuous low state of charge.
- Continuous operation of AC loads up to 100 W, with a power factor as low as 0.4 in ambient temperatures up to 60°C.
- Means to prevent cycling of the LVD until battery charging resumes.
- PV/wind selector switch. In the PV position, the PV is used to determine night and day operation and the light does not need a light sensor to control its operation. In the wind position, the light must have a light sensor switch in the AC circuit. This sensor can be provided separately or is sometimes integrated into the light fixture. The controller can intelligently determine sunrise and sunset from operation of the load and the controller's internal clock.
- Simple TEST push-button switch to turn on the AC output for testing the light, even during the day.

Features of the DC/AC Inverter

- LED indication of AC power output.
- Non-isolated converter. No transformer, high or low frequency, is used in the inverter, allowing for a very compact size and efficient operation.
- Power stage uses surface-mounted components to achieve the highest possible energy density, hence a small, easy-to-produce, low-cost package.
- Designed to specifically prevent DC injection into the lighting load.
- Designed to eliminate the need for electrolytic capacitors, a component that can impact long term reliability.

Common Features of the Integrated Controller

- The charger, load control, and inverter are all controlled by the microprocessor.
- Full protection against reverse connection of either the power source or battery. Reverse protection of the load is not required because the load is AC.
- Designed for operation in harsh environments and for rugged, long-term operation.
- Design MTBF greater than 10 years.
- Internal thermal protection.

- Operating temperature range –40 to +85°C, 0 to 100% relative humidity.
- Crystal clock operation for keeping track of time of day and accurate 60-Hz inverter output frequency.

Drawbacks of This Approach

- The AC output does not have a grounded conductor as is typical in 120-V, line-neutral systems. If a grounded conductor must be provided in a particular installation, then an isolation transformer will need to be added to the system. Product labeling will be required to indicate that both AC output wires are live relative to ground (60 V).

A Prototype Controller

Figure 13 shows a prototype of the system controller. One more revision of the design will be made before beta units are sent out for testing. It is expected that the final unit will be slightly smaller than the unit shown in the figure.

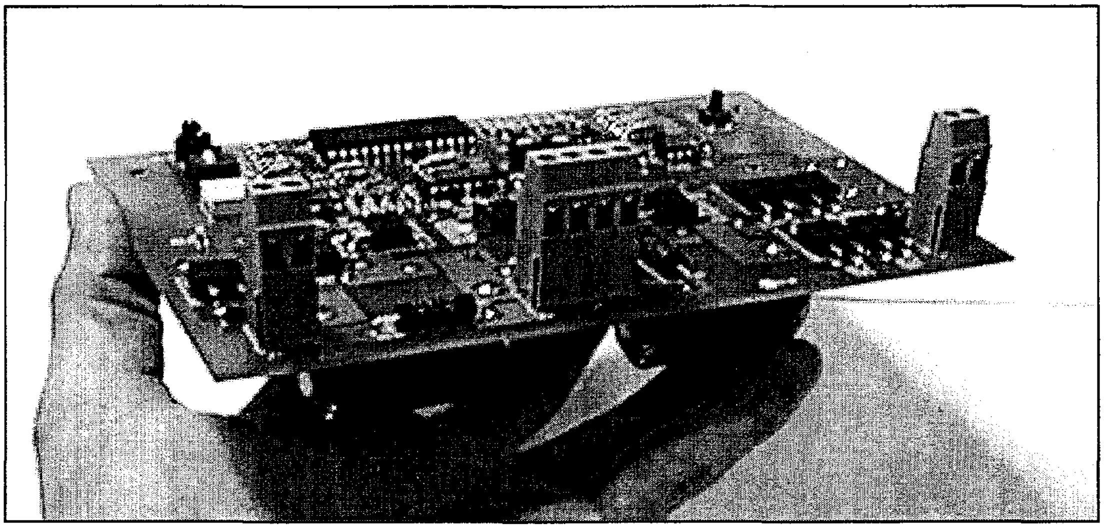

Figure 13. Prototype controller.

The final design of the controller will utilize surface-mounted components for compact design and lower-cost production. The controller above includes a dip switch for setting the type of systems in which it is installed. The system controller's appearance may be similar to that shown in Figure 14.

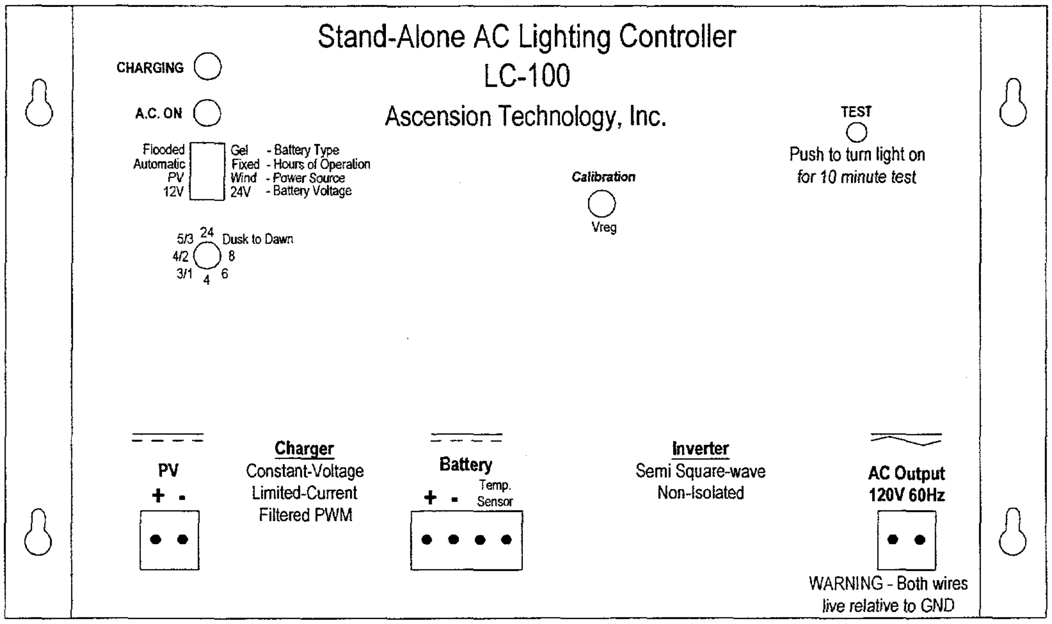

Figure 14. System controller.

Features of the Battery Charger

- Uses a true DC/DC 100-kHz PWM converter with output filtering to control battery charging current.
- Full protection against reverse connection of battery or power source.
- Three-stage charging profile
- Periodic equalization charging

Features of the DC/AC Inverter

- Uses a non-isolated DC/DC 100-kHz PWM boost converter with a low-loss, 60-Hz DC/AC inverter for shaping the output AC voltage.
- A semi-square-wave output is generated that is sufficient for powering AC lighting loads.
- Continuous operation for lamps up to 100 W at 60°C ambient, short-term surge rating is higher (to be determined).
- Designed to eliminate DC output, thereby preventing one of the potential failure modes in AC lamps.

How the Proposed System Addresses the Gaps in Technology

Reliability

The product will be thoroughly tested before introduction to the market. This testing will include beta testing at selected independent sites across the U.S. Testing will also include highly-accelerated lifetime testing (HALT) to ensure the design will meet the limits of electronic technology for performance and reliability.

The product will be protected against damage from moisture and other contaminants by using conformal coating or by encapsulating the circuit. The method of protection has not been determined yet. Because they are the least reliable system component, electrolytic capacitors will not be used in the design of the controller if possible.

The goal is to achieve a design with a MBTF greater than 10 years in field operation. Design for test is included in the design of the product to allow automated testing, both passive and active. All products shipped will be tested in the factory.

Cost—Level of Product Integration

This product is highly integrated for volume manufacture. There are no wires or cables or connectors used in the internal components of the product. All assembly is accomplished on a single circuit board. The charger and inverter share a single microcontroller.

Potential Buyers

Anyone who needs lighting in a remote location is a potential buyer. In the domestic market, electric utilities, local, state and federal government agencies, local communities, and property owners are some of the entities who would purchase systems for the following applications: parks, beaches, recreation areas, campgrounds, and remote street lighting. In the global market, electric utilities, local, state and federal government agencies, local communities, and property owners are some of the entities who might purchase systems for applications such as village lighting.

One customer who contacted Ascension Technology has an existing street lighting application for a village, but the diesel generator and electric distribution system has not been reliable enough to ensure operation of the lighting. They are considering using PV lighting to avoid the downtime caused by the diesel generator and distribution system.

Why Install Stand-alone AC Lighting Systems vs. Other Lighting Systems?

- Installation cost economics. The cost of extending power service exceeds that of installing a stand-alone system.
- Desire for reliable operation, independent of an unreliable power grid.
- Desire to use clean renewable energy, rather than fossil fuels.
- Lack of electric power infrastructure.

Market Potential Estimate

Estimating the potential market size of stand-alone lighting systems is difficult. Part of the difficulty is that a stable market has not yet been developed; creation of the market is still in its infancy. Many people have heard the anecdotal statement from IBM that the potential worldwide market for computers was about four. We know how accurate that early prediction was.

In 1995, the U.S. spent about $37 billion annually in electricity to power lighting loads.[7] This was about one quarter of the total energy consumption of the nation. If only 1% of that were diverted to the purchase and maintenance of stand-alone lighting systems, that would be $370 million per year domestically. Approximately 2 billion people worldwide are without electricity. If we assume the potential market is one lighting system per 1000 people per year, then the potential global market could be $2 billion per year.

There are approximately 416 National Parks, National Monuments, National Historic Sites, and National Recreation Areas. If we assume that these national locations represent 10 percent of all the parks and recreation areas in the United States, then there would be 4160 total such locations. If we assume that the average initial cost of a stand-alone AC lighting system is $1000, and that each of these sites purchases an average of one system per year, this would constitute $4.16 million annually. In 1990 there were 1.39 million farms in the United States. If we assume that 10% of those farms would purchase one stand-alone AC lighting system and would replace that system every 20 years, an annual market of $6.95 million per year would exist.

In the first nine months of 1998, Ascension Technology received inquiries for a total of about 2500 PV lighting systems. These customers were either told we were not prepared to provide systems at this time or are waiting for development of the stand-alone AC lighting system product. If we assume that one out of every five inquiries results in a system sale, and annualize the above inquiries, this would yield an immediate market of $670,000 annually.

Consequently, the short-term potential market is estimated to be between the hundreds of thousands to tens of millions of dollars annually for stand-alone AC lighting systems. Clearly there are some major assumptions in the numbers above. Certainly the actual market size will depend upon the cost, availability, and financing of such systems. Hopefully, these estimates will establish some boundaries on the potential markets for stand-alone AC lighting systems.

Table 4 was computed using the following assumptions:

- It will take twenty years to fully develop the potential markets listed above.
- The estimates above are overly optimistic by a factor of 10.
- The market growth will average 20% per year over the 20-year period.

Table 4. Estimate of Market Potential

Year	Global Gross Revenue ($ millions)
1999	7.4
2001	10.7
2003	15.4
2008	38.2
2018	237.0

3. Proof of Concept Testing

Failure Mode Testing of AC Lamps

The Failure Mode

The specific failure mode that has been investigated is that of DC current injection into an AC powered lamp causing early failure of the lamp. One reference suggests this mode of failure but does not quantify the effect:

> *"The AC lamps contain symmetrical electrodes. They are non-polar and must be driven by an AC voltage with a zero DC average current. If forced to carry a DC current, one electrode etches or erodes very quickly, and the lamp fails prematurely."[13]*

Another reference makes similar claims to problems with DC injection in AC lamps:

> *"Furthermore, the hot arc tube may suffer electrolysis problems over time in the presence of sodium ions and a DC electric field."[12]*

Test Setup

The intention of this testing was to verify the occurrence of a mode of failure in AC lamps that was postulated to occur in the time frame of weeks or years. A test method was conceived in which it was hoped the method would accelerate the time to failure. Because an HPS lamp's cumulative hours of operation before failure decrease as the number of starting operations increase, we chose a test cycle in which the lamp would be turned on and off many times per day.

Test 1

A 70-W HPS fixture, with integral lamp and ballast from Electripak® was used. The circuit shown in Figure 15 was used to turn power to the ballast on and off, and to count the number of cycles and hours of operation for the test fixture. The cycles and hours counters would not accumulate unless the fixture drew sufficient power to trip the current sense relay, which indicates that the lamp is operating. A capacitor and isolated DC supply circuit was used to impress a DC voltage on the ballast in addition to the AC power supply. The current limiting resistance of the test setup was used to control the amount of DC current injection into the lamp. Test results are summarized in Table 5.

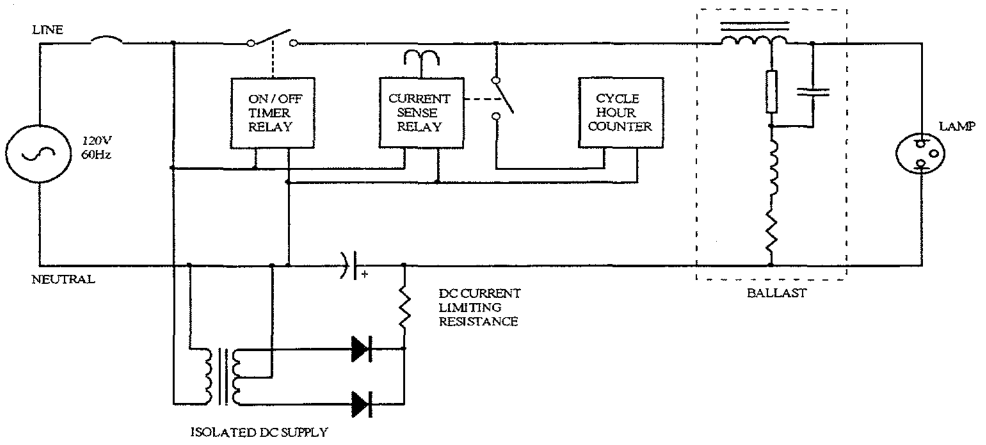

Figure 15. Test circuit.

Table 5. Test 1 Results

Lamp #	1	2	3	4
Manufacturer	Sylvania	Philips	Philips	Philips
Model	70W S62	C70S62	C70S62	C70S62
Limiting Resistance	6.8 Ω	13.6 Ω	3.4 Ω	No DC applied
Total # Cycles	20,772 cycles	13,531 cycles	13,457 cycles	5803 cycles
Total Cumulative Hours	597.67 hours	361.34 hours	357.54 hours	238.13 hours
DC Current Injected	0.14 A	Nm	Nm	0.00 A
AC Operating Current	1.64 A	Nm	Nm	Nm
DC/AC (%)	8.5%			
Bulb Failure	No	No	No	No
Inspection Notes	Some brown discoloration inside lamp at base. This brand of lamp comes with a silver coating at base of lamp when new.	No visible defects	A brownish discoloration at base of the lamp.	No visible defects

Because the results from this first test did not result in a failed lamp and because the lamps came from different manufacturers and the tests were started at different times, we decided to start the test again with lamps from one manufacturer at a higher level of DC injection.

Test 2

This second test ran for nearly 1000 hours by the time this report was written. As of the date of this report this second set of tests has not yet yielded a failed lamp. Test data is summarized in Table 6.

The amount of DC current injection was extremely high in this test. This was done to try to accelerate the time to failure. Surprisingly, Lamps 6 and 8 did not fail. The ballast for Lamp 7 appears to have failed immediately. New lamps were placed in the fixture, but would not light.

Table 6. Test 2 Results

Lamp #	**6**	**7**	**8**	**9**
Manufacturer	Sylvania	Sylvania	Sylvania	Sylvania
Model	70W S62	70W S62	70W S62	70W S62
Limiting Resistance	6.8 Ω	13.6 Ω	3.4 Ω	No DC applied
Total # Cycles	5,663 cycles	0 cycles	5,658 cycles	5,656 cycles
Total Cumulative Hours	936 hours	0 hours	935 hours	935 hours
DC Current Injected	0.643 A	Nm	Nm	0.00 A
AC Operating Current	1.768 A	Nm	Nm	Nm
DC/AC Amps	36.4 %	Nm	Nm	Nm
DC Voltage	11.1 V	11.1 V	11.1 V	0 V
AC Voltage	120.4 V	120.4 V	120.4 V	120.4 V
DC/AC Volts	9.2 %	9.2 %	9.2 %	0.0 %
Bulb Failure	No	No	No	No
Inspection Notes	Uneven electrode blackening observed.	Unit would not operate, bulb was replaced unit still would not operate, presumed ballast failure.	Uneven electrode blackening observed	No visible defects.

If one assumes that the failure mechanism is linear, that is, related to accumulated DC amp-hours through the lamp, then one can predict a maximum amount of DC current injection allowed into the lamp to achieve the product's specified 16,000 hour life. It appears that a DC current injection of (0.643A)(936/16000) = 0.038 A would be a safe level of DC current injection. This level may actually be higher if Lamps 6 and 8 last much longer in this test. This level may be higher or lower if the failure mechanism is not linear.

The amount of current injection must be related to the DC and AC voltages applied to the light fixture so that requirements for preventing DC voltage output of the inverter may be determined. The combined operating DC resistance of the ballast plus lamp is measured as 17.7 Ω. To keep the DC current injection below 0.038 A, the DC voltage must be kept below 0.673 V for this ballast and lamp. This voltage represents 0.56% of the AC voltage, and the inverter must be designed to prevent a DC voltage above this level under all lighting load conditions.

Lamps 6 and 9 are shown in Figure 16. Lamp 6 has undergone some electrode blackening due to the DC current injection. It is a little difficult to see in the pictures below, but is quite obvious in person. This blackening was clearly visible after several hundred hours, and is shown below after 936 hours. It is not yet known how much the life of this lamp has been reduced due to the DC current injection.

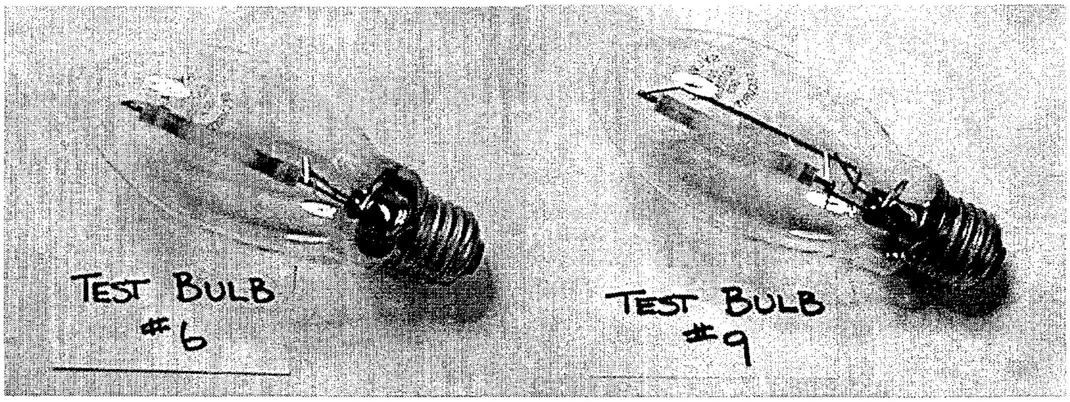

Figure 16. Lamps 6 and 9 during Test 2.

Can Conclusions be Drawn from these Tests?

Some preliminary conclusions have been made as discussed in the previous section. But it would be premature to apply these results to all AC lighting systems. More testing needs to be conducted, over longer periods of time, over a broader range of lighting loads, and over a wider range of DC current injection levels.

4. Conclusions

Development of a controller for intermediate-size stand-alone AC lighting systems appears viable, and would benefit U.S. industry in providing larger outdoor lighting systems than are commonly available today.

More testing is needed on lamp failure modes to determine specific requirements on the DC/AC inverter portion of the system.

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