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Solar Lighting—A New Industry

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Abstract

The use of natural light for illumination in buildings has great potential for both energy conservation and increased human comfort and worker productivity. A solar lighting industry is evolving that provides some of the components needed for solar lighting systems. Complete solar lighting systems are available from a few manufacturers for specialty applications. Currently the "industry" is a loosely-knit group of engineers, architects, designers, and manufacturers, mostly of components. A major problem is that there are *no* industry standards governing either illumination or energy performance of these systems. It is not surprising that the public knows little about the field. Suggestions are made for overcoming past limitations and for forming the solar lighting community into a coordinated industry. The main conclusion is that more organization and cooperation is needed within this new industry.

Introduction

It happens wherever you go: It's a bright sunny day, and the electric lights are on in schools, office buildings, stores, and most non-residential structures. There's plenty of natural daylight outside, free for the taking. But the most frequent choice is to use electric lighting. (Called "artificial lighting" by some, there is really nothing artificial about the light from electric lamps; so we prefer to call light from that source *electric lighting*.)

Typical practice is to rely solely on electric lighting. Windows are used only for the view and ambience; shades are shut when the sun is too bright. Often they are not opened again. This is a particularly energy inefficient practice, one that deprives the building's occupants of the many amenities of a view to the outside and daylight illumination of the interior. On hot days there is an irony to using electric lighting in the daytime: Electric lighting generally produces more heat than would be the case from an equivalent amount of daylight illumination. Here's how that works.

The luminous efficacy of both direct sunlight and diffuse sky light generally exceeds 100 lumens of light per watt of solar radiant flux. Compare this with a modern, efficient fluorescent lighting system, which has a system luminous efficacy of only 30-40 lumens of delivered illumination per watt of electrical input power. The fluorescent lighting system produces at least twice the amount of heat as daylight for the same level of illumination. In this case you have to pay for both the electric lighting *and* the cost to remove the unwanted heat (if the latter is not needed in heating the building). Typically 20 to 50 watts are needed to remove the heat from every 100 watts of electric

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lighting used [1]. This means that when the air conditioning system is being used, electric lighting costs on the order of ten times more in purchased energy than does solar illumination at the same level.

Here's how this 10:1 ratio was calculated. Some advanced fluorescent lighting systems have overall luminous efficacies in excess of 50 lumens per watt, a few as high as 70, but the world average is much lower than this figure. We use 33 lumens per watt as a representative value for the illumination *delivered to the needed areas*. For 100 lumens of illumination with daylight, approximately 1 watt of heat gain is produced, costing about ⅓ watt in purchased electricity to remove it, assuming a good air conditioner coefficient of performance of 3.0.

Compare this with the cost of operating an electric lighting system. For 100 lumens of fluorescent lighting, at a system luminous efficacy of 33 lumens per watt, 3 watts of purchased electricity are needed to power the lighting system, and another 1 watt of purchased electricity is needed to remove the 3 watts of heat generated by the lights. The ratio of these is 4 watts to ⅓ watt, or a 12:1 ratio, which is rounded down to 10:1 to be conservative. The situation is even worse with incandescent lamps, which have a system luminous efficacy close to 15-18 lumens per watt. This is the core reason why solar lighting systems make good energy and economic sense when their installation costs can be kept modest.

Electric utilities are generally required to meet peak demands whenever those peaks occur, including times when sunlight is most abundant and when much of the population is using electric lighting. Most utilities want to reduce their peak demands, to avoid adding generating capacity that will be idle for much of the time [1,2].

Both small and large companies around the world have recognized the potential for solar lighting systems to displace electric lighting energy consumption while providing very high quality illumination and other occupant benefits. A limited number of complete solar lighting systems can be found in the U.S. market. Fortunately, consumer interest in solar lighting is increasing steadily [2]. Results published from several studies suggest a strong preference for natural light, when compared with electrically produced light [1,2]. Positive health effects are also being documented.

As mentioned previously, the energy efficiencies of modern electric lighting systems have improved considerably in the last few years [3], but the penetration of these very efficient systems in the marketplace is limited. Although available, very energy efficient electric lighting systems are seldom used.

Given these circumstances, we now describe the current solar lighting industry in broad outlines. This description covers some of the common problems that have hindered the widespread market acceptance of the different varieties of solar lighting systems.

Definition of Solar Lighting

Solar lighting can be broadly defined as any use of sunlight or sky light for illuminating the interior of a building. The sun is the source of all daylight illumination, in the form of both beam sunlight and, following diffusion in the atmosphere and clouds, diffuse skylight. This solar radiation can be brought directly into a building as daylight, or it can be converted into electricity on-site, with the electricity being converted into electric light through an efficient electric lighting system. It has been estimated that solar lighting can supply up to 70% of the daytime lighting needs in this country [1,2].

The solar electric industry is already well-established, as is the industry making electric lighting systems to use the solar-derived electricity produced. Thus we here exclude solar powered electric lighting from further consideration in this paper, except for comparison purposes in the next section. Furthermore, traditional daylight illumination of building interiors through conventional windows and ordinary skylights is a well-established industry and widely used practice and is also excluded from discussion here.

What are here called solar lighting systems are mainly systems employing some essentially optical means for acquiring the sunlight, mostly from the direct beam rather than from the diffuse sky light component, another means for distributing this illumination over a modest distance, horizontally, vertically, or both, and a final means for spreading the light over the area of intended use inside the building.

These categories of solar lighting are illustrated schematically in Fig. 1.

There are two factors that make this market attractive. First, lighting accounts for 40-50% of commercial energy consumption and 10-20% of industrial energy consumption [4]. Second, electricity is one of the most expensive forms of energy [4]. These two factors imply that the size of the potential market is substantial, and that there is likely to be a reasonably short payback time for well-designed solar lighting technologies.

As anyone in the lighting industry will attest, the market is fiercely competitive. The very first consideration in the development of a new lighting product is its market potential. Solar lighting has to enter the marketing game in a big way if it is going to join the larger industry surrounding it, and with which it has to compete. There is no single company that has been able to pull this off—which strongly suggests the advantage of a joint effort. In the remainder of this article we hope to begin a dialog about this problem.

Overview of Solar Lighting Technologies

Some deep-seated difficulties have prevented the fledgling solar lighting industry from taking advantage of the sizable market opportunities existing around the world today. In order to understand these difficulties, it will be helpful to discuss the classification of the technology illustrated in Fig. 1. The two major classes of solar lighting systems, optical and photovoltaic, are contrasted in Table 1.

One of the challenges to the field today is getting building designers, specifiers, and owners to recognize that the photovoltaic class is but one possibility for solar lighting. The effort to market solar optic lighting systems and increase general awareness of their existence has been aided significantly by the recent rapid introduction of one type of solar lighting system into the U.S.

market. Sales outside the U.S. are robust as well. This is the simple cylindrical reflective tube extending from the roof to the ceiling of a building, known generically as *tubular skylights*. Known as a SunPipe™ and SolaTube™, among others, this technology is now widespread in the U.S. Other solar lighting systems, however, are little known and rarely marketed.

Table 1. Classes of Solar Lighting

Technical Class	How It Works	Principal Advantages	Principal Disadvantages	Commercial Maturity
Optical	Brings sunlight into a building for purposes of illumination.	Uses sunlight directly. Boasts good efficiency. Non-tracking systems are very durable and nearly maintenance free.	Some applications require both potentially expensive solar concentrators and expensive light-piping to distribute deeply into multi-story interior spaces. Tracking systems add to costs.	Varies from very mature for a few products to very immature for others.
Photovoltaic	Converts sunlight into electricity and stores it.	Potentially effective for all areas of a building and at night. Low-voltage wiring is inexpensive and easy to install.	Relatively high initial costs for PV array, batteries, and electrical control elements.	Very.

Another challenge facing the industry is to develop a synergy between the optical and photovoltaic classes. The synergy should be automatic, since any direct solar lighting system must be supplemented by an electric system for night-time use. Battery storage of solar electricity during the day, for use at night by very energy efficient luminaires, is an obvious way to deliver nighttime illumination using solar energy.

Yet another challenge is to develop simple methods for predicting solar lighting system energy and illumination performance. This is needed both for marketing and for determining compliance with energy codes. An approach to realizing this need is described subsequently.

There are four general methods for lighting directly by optical means. These methods are based on conventional fenestrations (windows, skylights, clerestories, and roof monitors), special window systems, skylights or solar pipes, and the more complex collection and distribution systems.

These methods, together with the photovoltaic method, are represented in the sketch of Figure 1.

Conventional fenestration systems are the most widely used systems for natural lighting [7]. Much experience has been gathered with this method. The special wall daylighting system shown in Fig. 1 is installed so that its input section faces the sun. Direct beam sunlight is then sent into the building, usually onto the ceiling, where the light reflects and diffuses downward.

A common skylight is basically a roof window. However, the direct beam solar gain normally produced can be a source of glare and localized overheating. These problems can be ameliorated by use of milk-white diffusing glazings or more sophisticated optical devices for controlling the admission and distribution of sunlight through what would otherwise be a conventional skylight. When a skylight is equipped with reflecting louvers or other active and passive means for controlling the admitted solar radiation, it enters the category of solar optical lighting systems, classed in Fig. 1 as a "roof fixture," as is the solar pipe mentioned previously.

The solar pipe consists of a highly reflective metal tube extending from just above the roof to just below the interior ceiling. The roof aperture is covered with a clear plastic or glass dome for weather protection, and the ceiling aperture is covered with a diffusing dome.

Special collection and distribution systems include many ways of collecting diffuse and concentrated solar radiation, putting this into a light pipe or other type of distribution system, and delivering it to an interior space. Special devices such as imaging and non-imaging concentrators and tracking or non-tracking mirrors at the collection end of this system provide greater quantities of light flux than the less sophisticated systems such as the solar pipe depicted in Fig. 1. The energy collected by these larger systems can be "piped" as far as 100 feet into a building [1].

The energy generated by a photovoltaic system is generally used for more than lighting and is especially cost-effective in remote locations that are off the electric utility grid. Such systems have great potential in developing countries (as do all other solar lighting systems).

Almost all of the methods for solar lighting have both passive and active versions. Passive systems require no additional energy or control for routine collection once they are installed. Examples include window wall systems and roof fixtures based on stationary reflectors.

Active systems have their own requirements for power and control, but they make better use of sunlight than passive systems. They are more expensive than passive systems. Examples include tracking devices that keep rooftop collector systems or photovoltaic systems aimed at the sun. Specific examples of different methods for solar lighting are presented in Table 2. Some of them are still experimental, while others are already on the market. All embodiments of solar lighting systems have one thing in common: For effective energy savings, electric lighting systems using purchased electricity must be equipped with some means of dimming their outputs or shutting them off when adequate solar illumination is provided. Fortunately, several "daylighting control" systems are on the market to accomplish this task. With these dimming systems, electric lighting levels are modulated according to the availability of natural lighting. These controls also can be used in conjunction with photovoltaic lighting systems to minimize battery power drain when natural daylight levels are adequate.

Table 2. Five Solar Lighting Examples	
Solar Lighting Method	Example
1. Conventional Fenestration	Windows, clerestories, roof monitors, skylights
2. Special wall daylighting system	Holographic window films [8], refractive fixtures [9], Stationary Projecting Reflector Arrays [10], “light scoops” [2]
3. Roof fixture	SunPipe [11], SolaTube [12], So-Luminaire [13], SunSeeker [14]
4. Rooftop collection and distribution systems	Heliostats that direct light into a light pipe distribution system
5. Photovoltaic lighting systems	Many commercially available components from a variety of manufacturers.

The past decade has seen great strides in all methods for solar lighting, most notably those incorporating conventional fenestration options. The National Fenestration Rating Council [15] is developing uniform procedures for rating the instantaneous thermal and optical properties, and the annual energy performances, of common configurations of windows.

Performance Standards

While there are different options for lighting with the sun's energy, there are no standards for rating solar lighting performance. Without such standards, one type of system cannot be compared objectively to another. This makes it difficult to choose one solar lighting installation over another.

Public acceptance and use of a building technology like specialty fenestration is largely guided by industry standards. When a contractor specifies a window installation, practical performance ratings are absolutely essential for meeting the client's expectations. Further, the ratings of competing products must be supplied in a consistent manner and must allow for comparisons among the different products. One of the unspoken truths of the current state of solar lighting technology is that except for conventional fenestration systems, none of the methods listed in Table 2 has come close to having an industry-wide standard. This is made more evident by the fact that there is no text, no guidebook, no catalog, no reference source whatever for specifying combinations of the five solar lighting methods.

Individual companies in an emerging industry often don’t want to talk much to their competition, since each company is intent on getting a bigger piece of the marketing pie. What they often fail to realize is that, by joining together, the size of the pie can be greatly increased, giving everyone in the industry a bigger piece, even if the relative proportions stay the same.

Until industry standards and guidelines for solar lighting are available, the consumer will have to rely more or less on luck in finding an architect or engineer skilled in solar lighting system design and specification. The practical consequence is that, as an industry, solar lighting remains in its infancy.

Research Needs

There are many areas where research is needed in any emerging industry. Many are in new product development, and are therefore likely to be jealously guarded by the individual companies involved. There are other areas, however, where research of a more fundamental nature is needed, the results of which should benefit the entire industry. Research in support of the development of industry-wide performance standards is but one example.

Perhaps the most important area where research is needed is in finding ways to predict the long-term energy and peak-load performances of these systems. The systems are so varied that it may not be easy to find one simple method of predicting long-term energy performance. This performance can be divided into three separate technical tasks.

1. **Illumination transfer characteristics.** For a given quantity and direction of incident beam solar radiation, and an angular distribution and quantity of diffuse sky radiation, one must determine how much light emerges from the system and in what directions. Next, one needs to know how this distribution of emergent light changes with changing illumination conditions. As the sun moves through the sky and as clouds partially or totally obscure the sun, how do these changes affect system output illumination?

2. **Instantaneous heat transfer characteristics.** To assess impacts on a building's HVAC system, the quantities of heat conducted through the solar lighting system to or from the interior of the building need to be known for a given indoor/outdoor temperature differential. The quantity of solar radiant heat gain admitted into the building by the system is also important. This heat is a beneficial addition on cold winter days and a detriment on hot summer ones.

3. **Annual overall energy performance characteristics.** Once the instantaneous light and heat transfer characteristics are known for a given solar lighting system, one needs to perform an hourly simulation of the system's performance, to permit predictions of its economic viability. In nearly every case, a solar lighting system will add to the cost of a building. Before a decision can be made to pay this extra cost, some assurance must be provided that the extra cost will be recovered through lowered operating expenditures over a reasonably short period of time.

In each of these three areas different approaches are possible. Looking at the first task, determining system illumination transfer characteristics, two approaches can be taken. The first is direct measurement. The system (or a small scale model of it) is illuminated by collimated radiation approximating the angular and spectral distribution of radiation from the sun. A goniophotometer is then used to measure the fraction of incident radiation emerging in different directions from each exit aperture after passing through the system. The direction of incidence is then changed and the goniophotometric measurement repeated. By this means a table of performance characteristics is developed with which one can determine the response of the system to any pattern of illumination from the sun and sky. No test facility of this sort exists, anywhere. Although such a facility would be of great benefit to the solar lighting industry, the cost is so great that it is unlikely that any current solar lighting system manufacturer will be able to finance and operate one. This is clearly an area for government support, possibly supplemented with pooled resources from the industry itself.

The Florida Solar Energy Center is constructing a goniophotometer for testing solar PV lighting systems. A future modification, to permit illumination of a solar optical lighting system from a variety of different directions, could be a cost-effective way for the industry to obtain a test facility.

The second approach to predicting illumination performance is calculation. Assuming that the optical properties and detailed geometric configurations of *all* components of a system are known, it is possible to simulate or mathematically model the passage of incident radiation through the system. The tests described above could be performed on a "virtual" basis, by calculations rather than measurement. Breault Research Organization of Tucson, Arizona has developed an advanced optical ray tracing program called ASAP that is capable of performing the needed calculations. The program is quite expensive, and it requires expert technical abilities and special knowledge to run it properly. This is another area where either government assistance and/or pooled resources could benefit the industry.

Considering the second item in the above list, thermal performance assessment, one can examine the significance of any thermal separation between the entrance aperture or interface with the outdoors and the interface with a building's conditioned air spaces exhibited by many solar lighting systems. In some cases, it is reasonable to assume that conductive heat transfer through the system will be negligibly small. In other cases, tests or calculations must be performed to determine whether the heat transfer is significant enough to be included in overall energy performance assessments, or if it can be simply approximated. This is another area where research is needed, but the needed research will be highly specific to each individual solar lighting system, since they vary so much in size, complexity, and geometry.

The third area of performance assessment might involve combining the instantaneous performances of the system with hourly solar radiation and weather data to perform a computerized simulation of the annual energy performance of the system. Although sophisticated building energy performance simulation programs exist in the U.S., such as DOE-2, BLAST, and TRNSYS, none of these has yet been modified specifically to include a variety of solar lighting systems. Such modifications, or developing whole new calculation tools, is another important research topic that should be of interest to the industry. This is another area where government support and pooled efforts can be helpful.

Toward Indices of Performance

Solar lighting systems have been around, though not widely used, long enough to permit a categorization of their performance characteristics.

System Efficiency. Three suggested definitions of *component efficiency* are introduced in the Appendix. Developing efficiency and other performance indices for all the lighting system types listed in Table 2 also will be important. Efficiency numbers have been defined for the various components of traditional photovoltaic systems [6]. However, more work needs to be done to determine how well solar optical lighting systems "fit into" a building's lighting needs.

Any measure of solar lighting efficiency can be defined on an instantaneous, hourly, daily, seasonal, or annual basis. The time period over which an efficiency number is defined is therefore an important issue to be addressed. Perhaps it will be possible someday to rate the average, peak, and "typical" levels of the lighting output power of a given system.

The overall goal of solar lighting design is to provide the required quantities of illumination as inexpensively as possible while reducing adverse impacts on a building's envelope and occupants, and to do so in a manner deemed attractive by most occupants. This multi-faceted goal will not be achieved unless a concerted effort is made by all constituents of the solar lighting industry.

Aesthetic Appeal and Other Human Factors. Lighting technology has a psychological dimension. A solar lighting device's placement, its overall appearance, and the degree of similarity that it bears to traditional luminaires all contribute to its potential acceptance and use. The color rendering performance of solar lighting systems is also of great importance. This must be recognized from the beginning in efforts to define performance criteria.

Pre- and Post-installation. Most of the lighting systems listed in Table 2 involve integrating an apparatus for collecting sunlight into the envelope of a building. Both the time and cost of installation generally increase with the size and complexity of the apparatus. Following installation, responsibility for interfacing the operation of the solar lighting system with that of the HVAC and electric lighting systems has not yet been delineated. Improper coordination can result in very bad system performance, both on an energy basis and psychologically.

Performance Tests. The engineering behind the collection and distribution of solar illumination has become increasingly clever and effective. In fact, there are so many different ways to design and "test" solar lighting devices that it is difficult to keep track of them all. In addition to the limits imposed by the purely physical laws that govern solar lighting, design criteria are constrained by human and installation factors as well as cost considerations.

Energy Ratings. In this age of increasing awareness of energy consumption, managers and planners require credible data when auditing the energy performance of a building. In many cases, the lighting systems in a building are subject to one or more governmental regulations. It is reasonable to anticipate a need to estimate, on an annual basis, the illumination and heating/cooling load characteristics of solar lighting systems. This will require methods for simulating the contributions of solar lighting to the overall energy performance of a given type of building under typical weather and solar availability conditions.

Currently, there is no standard method available for assessing the long-term energy performance of solar lighting systems. The experiences of the Illuminating Engineering Society of North America and the American Society of Heating, Refrigerating, and Air Conditioning Engineers in developing methods of assessing long term energy performance of buildings and their lighting systems should be of benefit in developing a standard for solar lighting systems.

What is astounding is that there are, as yet, no uniform standards for determining even the most basic aspects of solar lighting performance.

Conclusions and Recommendations — An Industry-Wide Solution

The current situation in solar lighting is complicated by industry's need for the disparate fields of expertise, listed below.

1. Architects and other specifiers who specialize in natural lighting
2. Designers of solar lighting systems
3. Manufacturers of reflectors, solar optical systems, and other component stages
4. Manufacturers of window systems
5. Manufacturers and specifiers of daylighting controls for electric lighting systems
6. Vendors of the various components and systems
7. Contractors responsible for installation and follow-up
8. Optics specialists with the tools and abilities to simulate the lighting and energy performances of solar lighting systems.

With all the problems inhibiting smooth introduction of solar lighting systems into both new construction and the retrofit market, it is unlikely that sales of such systems will expand rapidly in the near future. This situation can be aided by cooperation in the solar lighting industry. A Solar Lighting Industry Association has been formed in the U.S., and is being brought into the Solar Energy Industry Association. Such associations in other countries can be responsible for guiding the technology out of its current doldrums and into the mainstream of illuminating engineering and product sales.

A suggested mission, or set of goals, for solar lighting industry associations is hereby offered.

1. Identification and coordination of the major players, and of organizations that want to participate in the industry
2. Research into the development of turn-key product lines
3. Definition, development, and standardization of performance criteria, possibly with an eye towards certification procedures
4. Establishment of an industry informational network, including product and corporate directories, technical resources, compilations of case studies, electronic bulletin boards, and industry world wide web sites
5. Organization of educational efforts on a national or international level, with an initial emphasis on highly successful demonstration projects
6. Promotion of technology transfer initiatives
7. Search for resources to support research needed by the industry as a whole
8. Development of a portable information display for use in trade shows around the world
9. Search for funding associated with transporting and staffing the informational display at selected trade shows

APPENDIX Suggested Efficiency Measures for Solar Lighting Systems

Nominal efficiency numbers have been used for many years to characterize traditional types of solar energy systems [6]. In most cases, one is interested in the amount of heat that is exchanged, or in the quantity of solar electrical energy that is converted to another form. There have been, however, few attempts to define efficiency ratings for the collection and distribution of luminous flux.

One can usually distinguish the collection stage from the distribution stage of a solar lighting system. For simple windows, the outer glazing is the collection surface and the interior glazing is the distribution surface. The visible transmittance of the glazing system is a useful indicator of light transmission. The solar radiant heat gain of such a system is characterized by the solar heat gain coefficient (SHGC). The conduction heat transfer is characterized by a parameter called the U-factor, having units of watts per square meter and per degree of temperature difference.

Rooftop systems collect solar energy by way of special optical hardware, and they distribute the energy through ducts, pipes, or fiber optic networks. In these systems the thermal conductance is quite small and can in many cases be neglected. To a first approximation, the SHGC can be equated to the solar transmittance of the system, unless a substantial quantity of solar radiation is absorbed in the last transparent or translucent element of the system. In this case a significant portion of this absorbed radiation is likely to end up as additional heat gain in the building.

There will probably come a time when an even greater variety of distribution systems will be available for each type of light collector than is now the case. It would therefore be advantageous from a designer's point of view to have a separate efficiency number for each stage.

Efficiency terminology for the distribution components of HVAC systems have been developed and are available for consideration [17]. Drawing on standard solar energy terminology, three efficiency numbers can be suggested.

Collection efficiency. The ratio of the quantity of solar energy leaving the collection stage of a lighting system to the quantity incident on that collection stage.

Distribution efficiency. The ratio of the quantity of solar energy leaving the interior luminaires to the solar energy leaving the collection stage

Delivery efficiency. The ratio of the amount of solar energy leaving the interior lighting fixtures to the quantity incident on the collection stage. This may be calculated by multiplying the collection efficiency by the distribution efficiency.

These definitions should be refined for specific solar lighting systems. Then comes the task of creating standardized testing conditions and procedures for their measurement.

Besides indicating how much energy passes through a solar lighting system, the efficiency values can also indicate a system's tendency to share its solar energy with other systems in the building. All solar flux entering the conditioned space of a building produces heat, influences space-conditioning loads, and may be the cause of energy penalties. It is important to take these potential interactions into account in the design of the system and in the definitions of performance parameters. For example, even an efficient distribution stage may cause localized heating problems if the collection stage concentrates the solar flux too much on an absorbing element, or if the luminaires fail to distribute the solar flux over a large enough area in the room.

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Figure

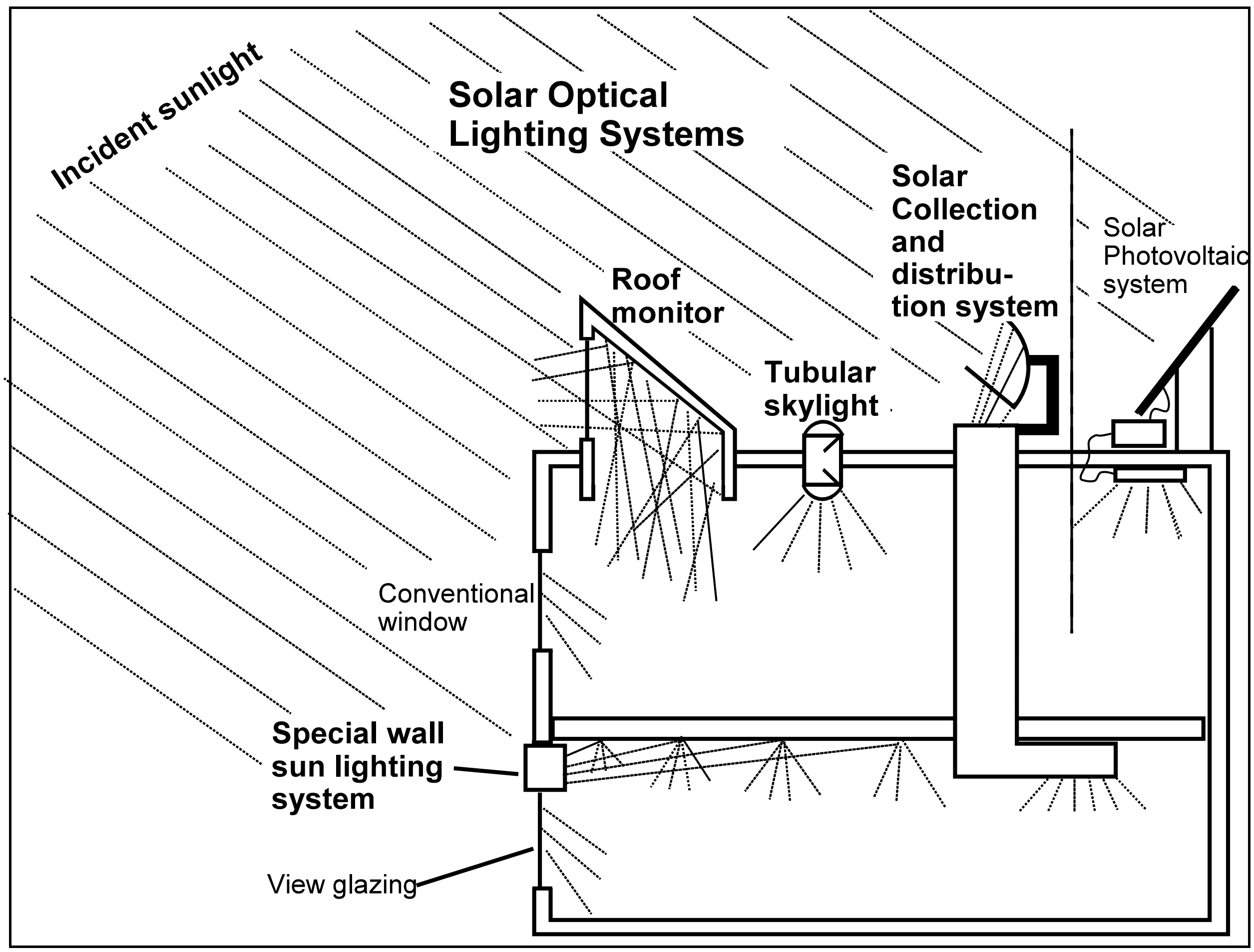

Figure 1. Classification of solar lighting systems, generically distinguished by whether they are solar photovoltaic (PV) powered electric lighting systems, solar optical systems utilizing sunlight and skylight directly, or conventional windows.