Focus Article

Solar street lighting: a key technology en route to sustainability

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Today's solar street LED lights are able to provide reliable, quality lighting both in developing and developed countries, thereby reducing light poverty and the economic and environmental costs of electric outdoor lighting. Rapid technical innovation and dramatic price reduction in the LED, PV module, and battery components, which has occurred in the last 5 years, will accelerate the penetration of solar street LED lights across the world. Applications will not be limited to countries with significant insolation only but will extend to Northern regions as well. This study provides a critical overview of a technology that will play an important role *en route* to global sustainability.

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INTRODUCTION

Solar street lighting based on photovoltaic (PV) electricity accumulated in digitally controlled, reliable batteries and used at night to power highly efficient light-emitting diode (LED) light sources is an advanced renewable energy technology increasingly used across the world to eradicate light poverty in developing countries and to provide inexpensive quality lighting in affluent areas of the world.[1]

Dramatic cost reduction coupled with technical hardware and software advances in all main components (PV module, LED lamp, battery, and microcontroller) has increased the adoption of these standalone systems, resolving historic reliability problems such as in the case of the 450 poles installed in southern Sicily in 2005 that went out of work a few months after installation.[2]

Today's solar street lighting is able to bring low-cost and environmentally friendly lighting to populations with no access to electricity, such as in the case of several hundred solar streets installed in 2010 in Conakry, Guinea, for years providing the only lighting in town.[3] Contrary to expectation (see below), the technology today can also be successfully used in Northern regions, providing financial relief to municipalities. Furthermore, glare-free LED lighting presents significant opportunities to mitigate skyglow and the ecological impacts of light pollution.[4]

This study intends to show the relevance of this critically important technology in the context of global efforts aimed to achieve a more sustainable development. Following an overview on the main technology trends, we provide economic arguments based on recent results achieved in different regions of the world with different solutions that demonstrate how solar lighting systems have evolved to become affordable, versatile, and reliable, pointing to a forthcoming boom in demand and utilization.

TOWARDS INTEGRATED, SMART SOLAR LIGHTS

The working principle of solar LED street lighting is simple. Solar cells, either on top of the pole or vertically integrated into the mast, generate electricity during the day. Electricity is accumulated in a battery through a charge controller, and when the sun has set, it is used to power highly efficient LED sources of white light with a small (typically 350 mA) direct

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current. It is emphasized here that the current output that powers the LED lamp comes from the charge controller (Scheme 1) and not from the battery so as to avoid its unsafe and undesirable deep discharge.

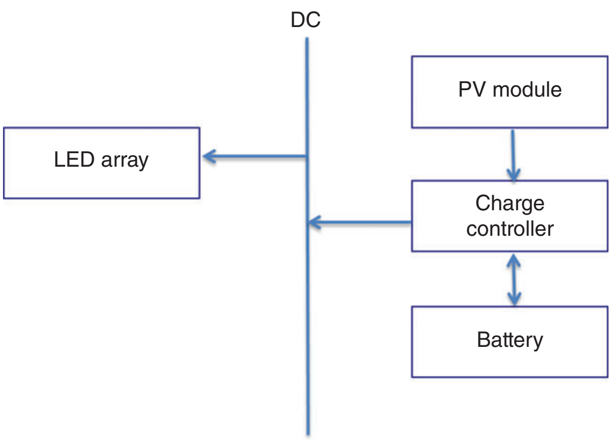
Certain manufacturers opt for burying the battery underground, whereas others leave the battery on the top or at the bottom of the pole (mast). Others, finally, elegantly insert the battery within the pole, a technical solution suitable for light, energy dense Li-ion batteries.

Solar street lights were initially used in remote locations and disaster-prone areas, with the poor luminous efficiency of incandescent or fluorescent lamps forcing the industry to over-size the solar lighting system, especially the solar module and the battery, to face the longest nights and cloudiest weather of winter.[5]

This lack of balance translated into wasting 50–60% of the energy generated throughout the year, high costs due to over-sized solar modules and battery, and poor appearance, confining the market for solar lighting to areas closer to the equator with the highest average levels of solar irradiation and temperatures that did not affect the performance of the incandescent or fluorescent lamps.

All this has changed in the last decade with the widespread diffusion of highly efficient solid-state LED lights. Today's reliable solar LED luminaires offer a documented long lifetime of at least 15 years (60,000 working hours, namely at least three times longer than conventional lighting discharge technologies) and are currently used to light a broad set of outdoor environments:

- Streets
- Highways



SCHEME 5 | Simplified block diagram of solar LED street lighting: PV module, charge controller (DC/DC converter regulated by a microcontroller), battery, and white LED array.

- Pedestrian and bike paths
- Gardens and parks
- Car parks
- Residential areas
- Architectural places
- Promenades

The advantages of this off-grid solar technology are clear: (1) no monthly electric bill; (2) no risk of electric shock thanks to the inherently safe 12/24 Volt circuit; (3) long-lasting and consistent high performance due to digitally controlled battery and LED; (4) high-quality, white, flicker-free light emitted by LED chips of high luminous efficacy (>130 lm/W) equipped with advanced optics for uniform light distribution; (5) no permitting, line voltage, trenching, wiring, transformer, and meter costs; and (6) lighting remains on in case of power outage.

To understand the scope of the innovation in this field, it is enough to compare a solar lighting system commercialized in the late 1980s with a typical state-of-the-art system installed today.

In 1988, villagers in Indonesia used incandescent bulbs coupled to a lead-acid battery powered, in turn, by an 11.1% efficient polycrystalline Si module (80 W).[6] After a decade, out of the 15 street lighting systems initially installed, nine were still working, with three having been converted to solar home systems and three out of order. Yet, pointing to the relevance of street lighting, all the villagers considered the solar street lights to be '*very useful and necessary in the village*.'

Today's state-of-the-art solar light systems use PV modules of no less than 16% efficiency, equipped with one or more bypass diodes for optimal production on cloudy days, multichip power LEDs of no less than 100 lm/W luminous efficacy, Li-ion battery seven times more durable than lead-acid batteries (see below), and digital micro-controllers for charging the battery and driving the LED light, resulting in solar street lights fully capable to meet demanding international lighting standards.

Furthermore, today's systems often have a wireless monitoring system to remotely monitor and manage each light (operating schedule, self-regulating dimming, power metering, performance monitoring).

In further detail, the latest design uses an integrated systems design approach, extracting the best performance from each component. Today's state-of-the-art charge controllers (or charge regulators) utilize a maximum peak power tracking (MPPT) charger that ensures maximum electricity production and efficient battery charging (compared to a basic charger, an MPPT charger transfers ~30% more charge from the module to the battery by increasing the charging current to the battery). A typical battery bank charge algorithm presents three different modes:[7]

- If the PV module available current is lower than capacity (in Ah), the converter will track the maximum power point (MPPT) in order to provide the highest current possible for the battery bank.
- If the PV module available current is higher than 0.1 capacity (in Ah), the converter limits the current to 0.1 CAh and disables the search for the MPPT.
- If the batteries are already charged, the control algorithm will apply a constant voltage level in order to keep the batteries (undergoing self-discharge) fully charged.

Newly developed digital micro-controllers, such as the *SO-Bright* introduced by Azzam in 2010,[8] feature a control algorithm that, besides maximizing the energy going into the battery, reacts to the storage capacity by comparing future energy needs with available storage, making incremental adjustments to the lighting profile to balance them.

As mentioned above, the poor performance of conventional lead-acid rechargeable batteries, with their high weight, short lifetime (3 years), and limited (50%) depth of discharge (DoD), coupled to faster than forecast cost decline of Li-ion batteries (about 14% a year between 2007 and 2014)[9] is leading to the widespread commercialization of solar street lights directly equipped with Li-ion batteries.

The initial higher upfront cost of these batteries is rapidly recovered due to a far longer lifespan and performance of the Li-ion technology, which is also much cleaner as well as safer for the environment. For example, a lithium titanate battery works well at temperatures between −20°C and 55°C, has an expected lifetime of 20 years, with 15,000 charge cycles (1200 cycles for the obsolete lead-acid battery), each complete in about 2 h (versus 6–7 h of a corresponding lead accumulator).[10]

As a further comparison, the cost of a single lithium titanate battery capable of storing and releasing 1140 Wh of electricity amounts to $987, whereas the cost of *two* lead-acid/lead gel batteries of the same capacity amounts to $811 (the energy density of the Li-ion battery is triple that of its lead acid counterpart). The lead-acid batteries must be replaced every 3.3 years, namely six times in 20 years, which translates into a four times higher cost for the obsolete lead-acid technology.

The technology trend towards integrated, smart solar lights is analogous to that taking place in building-integrated photovoltaics (BIPV).[11] According to this approach, rather than separately, the solar module, battery, controller, and the LED lighting source are all designed in one lamp. For example, the 40 W streetlight developed in China, shown in Figure 1, includes a 60-W, 18.2% efficient, mono crystalline Si module; a lithium ferrophosphate energy-dense battery; high-brightness white LEDs; and a micro-controller all integrated into a single lamp, also featuring light and motion sensors.[12]

An even more radical design approach involves the vertical integration of the solar cells along the mast of the lighting pole, such as in the case of street lights comprising solar cells integrated into the pole and protected by a tough polycarbonate shell, as shown in Figure 2.[13] The battery is vertically inserted in the concrete foundation of the pole, which has a passive ventilation system that cools the control and batteries, improving performance and system life.

The pole houses all batteries and control units for increased energy storage capacity, allowing up to three days of autonomy even in northern climates such as Denmark, while the advanced optics

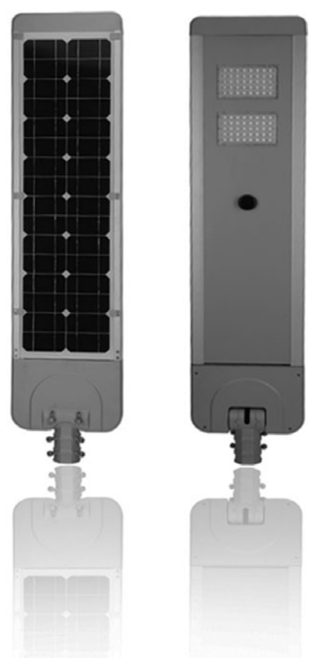


FIGURE 1 | One example of an integrated solar LED street lamp, including sensor, PV module, battery and controller. (Image courtesy of DEL Illumination, Shenzhen, China).

FIGURE 2 | Some of the 136 Monopole poles installed in Riyadh, Saudi Arabia. [Photo courtesy of Scotia, Vedbaek, Denmark).

employed in the LED lamp allows an extremely accurate control of the output and direction of the light, minimizing light pollution and allowing the use of lamps requiring less power to meet demanding street lighting standards.

INSTALLATION OF SOLAR LED STREET LIGHTS

The quality-driven process to properly install solar LED lights is guided by a preventive approach. Inspection of the site allows the insertion of the correct street area features in the lighting software, which, in turn, simulates different options. A typical state-of-the-art application provides a three-dimensional project with illumination levels, uniformity, luminance and shadows, spacing, and luminaire photometric curves.

Installation is then followed by a proper maintenance program:[14]

1. Site inspection
2. Project proposal with simulations reports
3. Approval and commissioning
4. Installation
5. Maintenance

Maintenance, though limited and low-cost, is very important, especially to address soiling of the PV module, which rapidly reduces electricity generation. For example, due to the proximity to the desert and high levels of volatile organic compounds in the air, losses of the output power due to soiling of fixed solar modules powering PV street lights in Baghdad reached 26% in just one month.[15]

Economic Aspects

Due to a dramatic fall in price and increase in efficiency of PV solar modules and LED lights that occurred in the last 5 years, most studies dealing with cost analysis of solar street lighting today are of historic interest.

For example, a study comparing the installation cost (in 2006) of 10-km roadway lighting with LED lights powered by grid and solar electricity included an $835 cost for a 167-W solar module ($5/W) and $1000 for a 100-W LED lamp emitting 7200 lm ($139/klm).[16] Eight years later, another economic analysis of solar roadway lighting carried out in Malaysia,[17] indicated more than halved costs for the solar module ($306, 140 W) and LED lamp ($410, 112 W).

Yet, by the end of 2015, the price of PV modules had dropped to $0.58/W.[18] In turn, the price of LED lights was less than $1 per kilolumen (Table 1),[19] decreasing at a rate of 28% per year between 2011 and 2015, corresponding to an 18% price reduction for each doubling of cumulative shipments.[20]

We remind here that the fact that a given technology follows a learning curve means that the cost will fall by a fixed fraction for each doubling in cumulative production as the curve characterizes the cost of manufacturing as a declining power law function of cumulative manufacturing.

Given such dramatic price reductions, it is perhaps not surprising that in a cost breakdown of the single units of solar LED streetlights completed in 2012 (Figure 3), the metal pole was already the most expensive component, accounting for 46% of the overall cost.[21]

With the advancements in the LED, battery, and PV technologies, the total price of a solar street system is decreasing at a rate proportional to that of the learning curve of the three technologies, compounded according to the relative weight of each component in the specific solar streetlight (21.5% for PV modules,[22] 18% for LED, and between 6% and 9% for Li-ion batteries[9]).

TABLE 1 | LED Package Price and Performance Projections[19]

	2015	2017	2020	Goal
Cool white efficacy (lm/W)	185	205	226	250
Cool white price ($/klm)	1.0	0.6	0.35	0.3

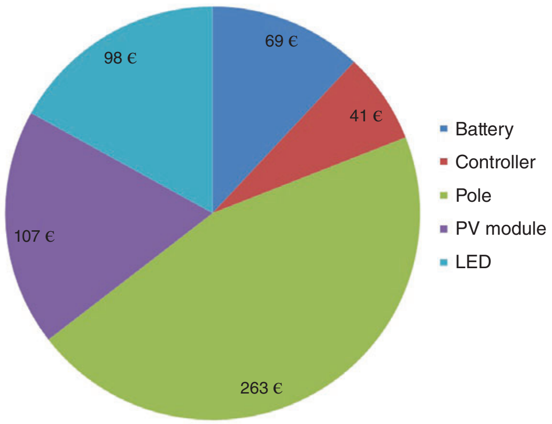


FIGURE 3 | Cost breakdown of the components of a solar street LED light in 2012 (Reproduced from Ref, 21 with permission).

FIGURE 4 | Harare's Enterprise Road during a rainy night on March 21, 2016. The city is completing a massive switch to solar lighting with 10,000 solar poles installed (Photo courtesy of Steven Chikosi).

Furthermore, the dramatic increase in the luminous efficacy of LEDs employed in commercial streetlights, from 70 lm/W in 2006 to 140 lm/W in 2015, has made the use of PV lighting also possible in northern areas, such as Denmark or Russia, where the first off-grid solar street systems for lighting streets, playgrounds, courtyards, and parks were installed in 2013.[23]

SELECTED LARGE PROJECTS

Solar street lighting is currently expanding at a fast rate across the world. The concomitant fall in the cost of PV modules, LED lights, and batteries has made the transition to solar outdoor lighting in developing countries more convenient than extending the electric grid.

In India, for instance, about 300 million people live in rural areas not served by the grid. The government thus recently took initiative to bring solar lighting to said rural regions. Two LED solar street lighting contracts were awarded in late 2015 to a major solar streetlight manufacturer to provide more than 76,000 solar LED street lights across 800 villages in Uttar Pradesh that will be lit with LED luminaires emitting 1200 lumen (absorbing 12 W, with lead-acid battery charged by a pulse width modulation charger). Small towns and villages of Manipur, instead, will be lit with 1400 solar LED lamps emitting 3500 lumen (absorbing 43 W, with lead battery equipped with MPPT charge controller mounted on a pole capable of withstanding strong winds).[24]

In Guinea, in 2015, the government started a nation-wide solar lighting campaign with a total of 30,000 solar streetlights to be installed in more than 300 towns and villages. Since late February 2015, every 3 days, a new neighborhood is given access to outdoor solar lighting.[25]

In Zimbabwe, the capitol Harare started the installation of 10,000 solar-powered streetlights in 2015 (a $15 million project, translating into a $1500 cost for each pole, including installation). Streetligthing was also a measure used to halt a recent rise in street crimes and enhance overall road safety (Figure 4).

In Brazil, in 2015, a civil engineering company completed the installation of 4310 solar street lighting poles (supplied by a large PV module manufacturer) that now provide excellent white light for 73 km of the highway connecting the five main highways crossing Rio de Janeiro (Arco Metropolitano do Rio de Janeiro, Brazil's largest highway). Each streetlight includes a 150-W LED lamp, three 250-W solar modules, one MPPT controller, a photocell (light sensor), a pole with mounting structures, and four 240-Ah lead-acid batteries.

Another benefit identified by the local government when opting to install 3.2-MW off-grid solar lights was to avoid overburdening the local electric grid.

PERSPECTIVES AND CONCLUSIONS

The global boom in solar photovoltaic energy[26] is disrupting the way in which centralized electricity systems operate.[27] Similarly, LED solar streetlights coupled to economically viable (and now technically improved) electricity storage solutions will drastically affect the street lighting market.

The two main limitations of solar street lighting (the poor performance of lead-acid batteries and the poor luminous efficacy of incandescent lamps) are now resolved by highly efficient LED lights and Li-ion batteries of unprecedented lifespans coupled to the digital technology of new micro-controllers. With today's LED lights requiring such low amounts of power, market opportunities will abound not only in sunny countries but also in Northern countries where high electricity costs are forcing local authorities to either switch off or dim lamps. The city of London, for example, is currently evaluating two such advanced streetlight poles similar to those previously installed in Denmark or in the Arab Emirates (Figure 2).

Money not spent by municipalities and governments to pay the electricity bill may be reinvested, for example, in social programs or in refurbishing existing infrastructure. In developing nations, thanks to solar street lighting, communities can benefit from quality illumination meeting international lighting requirements and available round the clock including during frequent power outages.

In 2014, a reputed business publication was surprised to notice the absence of a market study on solar street lighting despite the fact that a single Florida-based company, in 20 years up to 2013, had installed 60,000 systems in 60 different countries.[28] One year later, in the first such global market report,[29] the technology was found 'still in the innovation phase with standardization of solar street lighting systems not yet implemented leading to over-designing, under-designing or the lack of quality.'

The report also found that the solar street lighting industry was mostly located in China and India, with successful implementation of many local projects in the southern states of the US as well as in Europe and the Middle East.

We argue herein that with the rapidly growing demand that will follow successful large projects, such as those briefly mentioned in this study, large PV module manufacturers will enter a rapidly growing market in which orders will be measured in MW, such as in the case of the Rio de Janeiro highway. At the same time, new companies specializing in manufacturing advanced solar streetlights meeting demanding aesthetic, reliability, duration, and lighting quality requirements will also thrive.

There is still considerable scope for improvement through embedded sensors and wireless remote control, which could considerably increase energy savings (for instance, during the 'Lumisol' research project carried out in Portugal, targeting the African outdoor lighting market, about 75% energy savings were measured with the use of a presence detector).[30] Better sensors in the micro-controller will enhance the rate and accuracy when reading input and output voltages and currents, whereas improvements in the algorithms controlling battery charging and discharging, and the current powering the LED array, will provide an extended charge of the battery and a longer lifespan of the LED lights.[31]

As put by Maia Alves and co-workers,[32] it is completely worthless that street lighting remain on all night at the same level even when no one is there to use it. Thus, the introduction of intelligence in street lighting poles (using presence sensors) will allow a significant (>50%)[32] decrease in energy needs as well as a cost reduction as both solar panel and battery energy requirements will be lower.

Finally, as the efficiency of LED lights continues to grow, the installed PV power will be made available for other uses, such as cell phone, tablet, and portable computer charging, after the pole's battery is fully charged.

In conclusion, with the price of PV modules, LED lights, and batteries falling at quick rate, this clean technology will find widespread adoption across the world. Reviewing recent progress and selected applications in different countries, this study provides an overview of an important technology capable of eradicating light poverty and lowering the economic and environmental costs of conventional street lighting.

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