Reliable LED Lighting Technologies

Key Factors and Procurement Guidance

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***Abstract*— Lighting systems have the ability to transform the economic and educational infrastructure of disadvantaged communities, and eradicating "light poverty" has become one of the primary goals of the International Year of Light 2015. Solid-state lighting (SSL) technology, based on light-emitting diode (LED) light sources, has emerged as the next generation of lighting technology, with a current global market penetration of roughly 5%. This paper will report on recent research on understanding SSL lighting system reliability (failure modes, environmental stressors, electrical power quality); discuss the implications of SSL technology reliability for providing lighting services; and suggest practical approaches to ensure SSL reliability to benefit humanity. Among the key findings from this work is that LED sources can be extremely reliable, withstanding a broad range of environmental stresses without failure. Nonetheless, SSL lighting systems can have a negative impact on electrical power reliability, as well as on the affordability of lighting services, without attention to the quality of the accompanying power infrastructure. It is therefore critical to ensure that the performance of the power supply electronics used in lighting systems is matched to the quality of the power source, when evaluating energy efficient lighting choices.**

Keywords—LED light source; SSL lighting system; reliability; procurement guidance

I. INTRODUCTION

Electric lighting systems are an integral part of daily life for those with access to on- and off-grid power. Eradicating "light poverty" is essential to development in disadvantaged communities and has become one of the primary goals of the International Year of Light 2015. Developing countries in Asia and Africa face the critical challenge of expanding and transforming the current electrical power infrastructure into one that can accommodate technologies such as lighting that are essential to repositioning the local economy to benefit its citizens. However, the rapid rise of electrical lighting systems, without attention to the accompanying power infrastructure, can have a negative impact on electrical power reliability.

Solid-state lighting (SSL) technology, based on light-emitting diode (LED) light sources, has emerged as the next generation of lighting technology and has the potential to meet worldwide lighting needs at a significant reduction in energy consumption. The Global Energy Efficiency Accelerator Platform estimates that a global transition to a mix of efficient lighting technologies would save over \$120 billion annually in avoided electricity bills. through a reduction of over 1,000 TWh of electricity every year. This change would also save \$230 to \$425 billion in avoided investment in 280 large (500 MW) base-load or 520 large peak-load power plants [1]. Leapfrogging to LED lamps in all sectors by 2030 would cut global electricity consumption for lighting by more than 52% and avoid 735 million tonnes of CO_2 emissions each year. Installing LED technologies in homes could cut energy bills by EUR 5 billion on the African continent alone [2].

However, solid-state lighting technologies have only achieved a worldwide market penetration of 5%, indicating that there are still constraints and opportunities to be addressed [3]. Demonstration of the reliability of SSL devices is one of the most significant impediments that must be overcome to realize the energy savings potential of SSL [4]. Further complicating SSL reliability is the fact that the device is attached to an electrical grid of varying quality and subjected to voltage spikes and surges. This is especially critical in countries such as Nigeria or the Democratic Republic of Congo, where the quality of the electrical power grid can adversely impact the performance of SSL lighting. Underfunded, unstable and unreliable electricity grids can cause early LED failure, if not taken into account in LED lighting device design. This paper will discuss the impact of SSL technology reliability on the potential of lighting services to benefit humanity.

II. LED RELIABILITY

A. *Potential Failure Modes for LED Devices*

The failure rate of electronic parts is typically divided into three stages in the "bathtub" curve model of failure rates, and this simple model is a useful starting point for considering SSL technology failure:

- Stage 1 (Burn-In): Failure rate decreases in time, as defective products fail early, due to intrinsic design, manufacturing or parts defects;
- Stage 2 (Useful Life): Extended period of constant, generally low, failure rate due to random failures;
- Stage 3 (Wear-Out): Rapid increase in failure rate as a result of materials degradation caused by extended wear and aging.

It is imperative for standards and warranties to address burn-in and useful life failures (Stages 1 and 2). The high reliability of the LED light source observed during accelerated life testing under extreme conditions suggests that they will have a low probability of random failure in the field during normal use (Stage 2), that elements of the luminaire other than the LED light source are more likely to fail first, and that properly designed and installed SSL luminaires can be expected to have long lifetimes under normal operating conditions [5]. Consequently, a systems approach (including LEDs, drivers, optics and other components) is needed to evaluate the long term performance of SSL luminaires (Stage 2 and Stage 3).

Unlike traditional light sources, LED light sources often do not fail in a “lights-out” mode (i.e., complete darkness). Instead, the light produced by LED sources generally fades or changes color with time, and “failure” can be defined as having occurred when the lighting levels no longer meet the requirements of its intended purposes. This change in lumen maintenance often follows an exponential decay as given in equation 1:

$$\Phi(t)/\Phi(t=0) = Be^{-\alpha t} \qquad (1)$$

where $\Phi(t=0)$ is the initial luminous flux, $\Phi(t)$ is the luminous flux at time t, B is a pre-exponential factor approximately equal to 1, and α is the decay rate constant. The process for calculating B and α are given in Illumination Engineering Society of North America (IES-NA) Technical Memorandum TM-21 [6], and this information is often available from LED manufacturers.

Such changes in light color and intensity can be caused by changes in the LEDs themselves [7], but are more likely to be caused by changes in the optical materials used in the luminaires and lamps incorporating LED. For example, plastics like polycarbonate that are used in secondary lenses may yellow under certain conditions, reducing luminous flux and shifting the color of the emitted light [8]. In addition, a variety of stresses, such as excessive heat and/or humidity, high particulate levels, corrosive environments, and poor electrical power quality, can have a significant impact on lighting system performance.

RTI International, under funding from the U.S. Department of Energy, has been studying failure modes and reliability of SSL technologies and has developed models for the impact of some of these stresses on lighting system reliability. Among the key findings from this work is that LED sources are extremely reliable and can withstand a broad range of environmental stresses without “lights out” failure. This research has also shown that the performance of the power supply electronics can varying widely from product to product and is often a limiter in SSL device reliability [9]. To reap the benefits of SSL technologies, therefore, it is critical to consider electronic reliability when evaluating energy efficient lighting choices.

B. Accelerated Testing for LED Devices

Since properly-designed luminaires and lamps can survive many years of use in normal operating environments, accelerated stress testing (AST) is used to speed up degradation of the luminaire and create failures at a much faster rate than would occur in normal operating conditions. AST methods use one or more environmental stressors at elevated levels, typically:

- High temperature (between 45°C to 125°C)
- Low temperature (between 0°C to -50°C)
- High humidity (up to 90%)
- Electrical line voltage variations
- Vibration
- Particle exposure.

Often, AST testing protocols will incorporate multiple environmental stressors, such as temperature cycling (e.g., cycling temperatures between -50^{o}C and 125^{o}C), combined with heat and humidity testing (e.g., continuous exposure to 85^{o}C and 85% relative humidity).

Pacific Northwest National Lab (PNNL) published some of the first publicly available AST results on LED products [10]. In this study, simultaneous combinations of electrical, thermal, vibration, and humidity stresses of increasing magnitude demonstrated that LED-based products can be more reliable than conventional lighting sources. RTI International, in association with the LED Systems Reliability Consortium (LSRC), tested commercial luminaires using a highly accelerated life test (HALT) also known as the “Hammer Test”. In this test, commercial 6” downlights were subjected to a series of sequential environmental stresses, including temperature cycling, wet high temperature operational life test (WHTOL), and high temperature operational life test (HTOL) at 120^{o}C. This investigation demonstrated that commercial mass-produced luminaires were robust, even under the harsh conditions of the Hammer Test. When device failure did occur, it could generally be traced to electrical components such as printed circuit boards, solder joints or other electrical connections [5].

More recent publications from PNNL examined the lumen depreciation and color shift of commercial A lamps (15 LED, 1 CFL, 1 halogen) and PAR38 lamps (32 LED, 1 ceramic metal halide, and 3 halogen), which were monitored in a specially developed automated long-term test apparatus (ALTA).

On average, the lumen maintenance of the A LED lamps monitored in the ALTA was better than either of the benchmark lamps (i.e., CFL and halogen), but there was considerable variation from product to product. While three LED A lamp models had average lumen maintenance above 99% at the end of the study period (7,500 hours), two products had average lumen maintenance below 65%, constituting a parametric failure. These two products, along with a third, also exhibited substantial color shift, another form of parametric failure [11]. Beyond these failures, under the elevated (45°C) ambient test conditions, the lumen maintenance of nearly half of the A lamp products was sufficiently low at 6,000 hours that they were unlikely to have lumen maintenance above 70% at their rated lifetime (in most cases, 25,000 hours).

A similar examination of PAR38 lamps demonstrated that the majority of the LED lamps exhibited high lumen maintenance (between 90% and 98%) and all LED lamps exceeded 70% lumen maintenance after 14,000 hours of testing in the ALTA. The color shift of most of the PAR38 LED lamps was less than the EnergyStar threshold, although two LED products exhibited excessive color shifts and were parametric failures [12]. In contrast, the conventional lighting technology products (i.e., CFL, halogen, and metal halide) generally had lower lumen maintenance than the LED products, and all of the halogen lamps tested failed during testing.

C. *LED Device Driver Electronics Reliability*

While lumen maintenance and color stability are important considerations for LED device lifetime in all environments, electronics reliability is often the dominant failure mode, especially in situations with highly variable electrical grid quality. Line transients and voltage surges and sags have been shown to result in increased failure rates for LED devices [13].

Many LED drivers use switched mode power supplies to convert grid voltages to the appropriate power levels for LED operation. As shown in Fig. 1, electrical failure of these switched mode power supplies is often concentrated in two driver components, the metal-oxide semiconductor field effect transistors (MOSFETs), used for switching, and the capacitors. Knowledge of the failure modes of these components can help to design products that survive in demanding situations, such as volatile power grids.

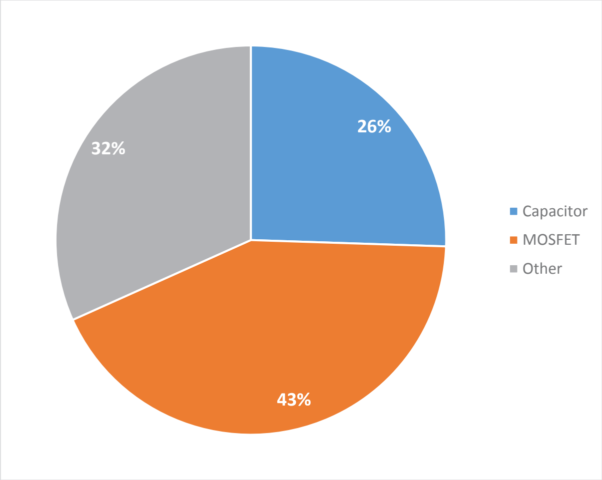

Fig. 1. Breakout of electrical failures of more than 100 SSL devices in accelerated stress testing.

MOSFETs are highly sensitive to voltage variations from the load, excessive temperatures and inadequate or poor power-supply bypassing [14]. In general, there is a significant amount of variation in MOSFET characteristics among LED device manufacturers including the type of MOSFET package, heat dissipation properties, heat sink designs, and the proximity of other heat sources. Good designs will allow the MOSFET to operate efficiently under most conditions and to direct excess heat to a sink for dissipation. If these precautions are not followed, high junction temperatures in the MOSFET will ultimately lead to device failure as shown in Fig. 2.

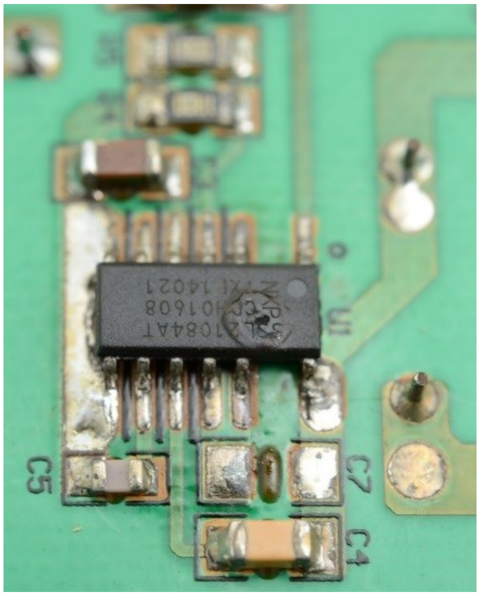

Fig. 2. Failed MOSFET from LED luminaire driver circuit. Excessive heat buildup in the MOSFET caused the plastic encapsulant to distort.

Capacitors are also used to store and discharge energy in electrical circuits and to smooth electrical ripples. In addition, input capacitance is also the cause of inrush current when an LED driver is first turned on. These inrush currents can create transients that damage electronic devices if not properly dissipated. Because of the energy stored in capacitors, they are often a leading cause of failure in SSL drivers and may also contribute to failure of other components such as MOSFETs. Common electrolytic capacitor failure modes include voltage stress (e.g., high voltage transients) and excessive temperatures.

Fig. 3. Failed electrolytic capacitor from an LED luminaire driver circuit. Failure resulted in venting of the electrolyte as shown by the brown electrolyte residue on the printed circuit board and the breech in the vent on the top of the capacitor.

Generally manufacturers are aware of these limitations of capacitors and take several steps to improve product reliability including:

- Derating of electrolytic capacitors (often 2X or more);
- Using high quality caps (minimum 105°C rating);
- Limiting use of electrolytic capacitors to low voltage and/or low ripple circuits;

- Avoiding placing capacitors near heat sources on either side of the board.

Another approach to increase driver reliability is to use film capacitors in circuits that are anticipated to be more susceptible to poor line quality and transients. Film capacitors are better able to handle voltage stresses due to their “self-healing” properties [15]. If these precautions are not followed, capacitor failure such as shown in Fig. 3 will occur, and the driver will either cease to operate completely (i.e., “lights-out failure”) or produce a lower lighting level due to a reduced LED supply voltage.

III. IMPLICATIONS FOR PROVISION OF LIGHTING SERVICES TO BENEFIT HUMANITY

Hundreds of millions of people lack basic access to lighting for task, general and community purposes, and lighting electricity demand is a burden on fragile electricity grids. Taking the African region as an example, this section briefly describes some implications of SSL technology for poverty alleviation and economic growth. Access to electricity in Africa is limited to about one-third of the population (and only 10% in rural areas) and an average per capita installed capacity of only 0.015 kW. Most African countries have struggled to keep up with the growth in demand of electricity, and lighting is a major source of peak demand and greenhouse gas (GHG) emissions.

If reliabile, LED technology – both LED lighting and other applications, such as LED-backlit TVs – can be an important tool to improve energy access in Africa, while helping to remove subsidies and creating local employment opportunities. According to a 2013 analysis by the International Monetary Fund, effective power tariffs are set 30% below the historical average cost of supplying electricity in sub-Saharan Africa (excluding South Africa) [16]. In addition, transmission line losses averaged 25% and the average collection rate was 85%, with as many as 60% of poor households not paying their electricity bills [17].

Under such conditions, and given the sub-Saharan Afican average electricity tariff of US$0.17/kWh, every kWh of power used represents a fiscal loss for the utility. Take the example of a community of 100,000 households with limited electricty access living in an urban slum in Africa, each of which might use 65 kWh/y of electricity to power a single 40W incandescent lamp and share a 60W TV with three other households for three hours per day.[1] Assuming that 60% of these low-income households had illegal electricity connections and did not pay for their electricity, the utility would lose just over US$1.5 million each year on electricity supplied (or US$15 per household), as a result of 30% underpricing, 60% non-paying customers and 25% line losses (Tab. 1).

TABLE 1. LED IMPACT ON MINIMUM ACCESS ENERGY SUPPLY

COMMON ASSUMPTIONS		
Customers	100,000	households
Lighting service level	450	lumen
	3	hours/day
TV service level	3	hours/day
Cost of geneation	0.24	US$/kWh
Residential tariff	0.17	US$/kWh
Line losses	25	percent
ELECTRICITY DEMAND (kWh/y)		
	Baseline	**LED Lighting**
Household electricity demand	65	25
Lighting	44	4
TV	21	21
HOUSEHOLD FINANCIAL (US$)		
Annual electricity bill	11.05	4.25
Annual savings (paying customers)	0	6.80
Cumulative savings over years	0	34.00
UTILITY FINANCIAL (US$/y)		
Paying customers	40%	90%
Revenues	$442,000	$382,500
Generation cost	$1,560,000	$600,000
Supply cost (inc. line loss)	$1,950,000	$750,000
LED cost	N/A	$500,000
Profit (Loss) Year 1	($1,508,000)	($867,500)
Profit (Loss) Future Years	($1,508,000)	($367,500)
Balance after 5 years	($7,540,000)	($2,377,500)
ELECTRICITY SAVINGS		
Annual Electricity savings (kWh)	0	4,000,000
Annual Electricity Savings	0	62%
Additional households served (no LED)	0	61,538
Additional households served (with LED)	0	160,000

If the utility instead outfitted these grid-connected households with a single high-quality LED that delivered the same 450 lumens using only 3.5 W at a cost of US$5 per bulb, the financial gains to both the utility and the paying customers would be significant. The utility benefit is due to avoiding losses associated with meeting electricity demand, as well as the assumption that the share of households that are both willing (in order to benefit form improved LED lighting service) and able to pay their more affordable electricity bills would increase from 40% to 90%.

In addition, the electricity consumption of these 100,000 households would decrease by 62%, immediately freeing up enough energy (4 GWh/y) to double the number of customers served or the amount of energy that a household could afford to purchase, with the same installed capacity. Additional gains for households and utilities are achievable by widespread deployment of today’s LED-backlit television technology, with on-mode power demand of <20W, resulting in 70% energy

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[1] This level of energy services corresponds to the minimum access case adopted by the Global Energy Assessment scenario for households [18].

savings relative to the prior generation of LCD technology, with no incremental cost.

Achieving universal energy access in sub-Saharan Africa will require installed capacity across all sectors to grow by double digits annually over the next 20 years, at a cost of US$73 billion annually [17]. Serving more customers (or raising the energy service level enjoyed by existing minimum access customers) without having to build new generation capacity is therefore a prime reason to consider LED technologies as the "fuel" for efficiency power plants. LED lighting products can essentially be considered components of electricity supply systems (be they off-grid solar home systems, micro-/mini-grids or national power grid connections) that improve overall productivity of the energy system.

These simple calculations show how important LED technology can be for developing country efforts to eliminate energy subsidies, achieve universal electricity access and alleviate poverty. However, successful market transformation requires that innovation strategies support the development of reliable solid state lighting technology and that market development receive the same priority as policies to phase-out obsolete and under-performing technologies.

Philips Africa Innovation Hub

Nairobi serves as the headquarters for the Africa Innovation Hub established by Philips in 2014. Today an estimated 560 million Africans live without electricity. To improve access to lighting in Africa, the Innovation Hub is developing new consumer products using the combination of solar power and energy efficient LED technology. These products are optimizing the efficiency of LED, its performance in light output and light distribution. New go-to-market models are also being established to ensure these solutions become accessible to people that would not be able to afford them otherwise.

The Hub currently employs over 40 full-time employees, spread across the African continent and The Netherlands, and is growing fast. It consists of two parts:

- Philips Research Africa, currently consisting of about 15 scientific researchers, who work to create new ideas and help bring them to scale. The research hub works together with local African innovation-eco systems and other Philips Research hubs across the world.
- Africa Incubator, designed to take ideas from pilot to scale, using a team of corporate (social) entrepreneurs that are working within Philips with the freedom to create new inclusive business models, which can later be integrated into the traditional Philips organization.

The Hub concentrates on scientific and user studies to develop locally relevant products, solutions and services, tailored to the African market.

IV. ROADMAP TO ADDRESS RELIABILITY AND LIGHTING ACCESS ISSUES

Innovation strategies might include supporting the development of high reliability products suitable to developing country conditions, preparing for the successful introduction of solid-state lighting (awareness, surveillance, compliance strategies), encouraging market transparency through product data access, creating and aggregating demand (for both luminaires and lamps), and promoting local supply chain and business model innovations.

Whereas larger markets like South Africa and Nigeria are now inundated with LED products, the availability of LED lamps in smaller countries lags that of CFL for the time being. Preventing poor quality lamps and fixtures from spoiling African markets remains a challenge. Trust is lacking in new technologies due to past failures of efficient lighting products (e.g., CFL lamps, off-grid solar LED lanterns/home systems) to perform according to supplier claims.

A. LED Standards and Design Specifications for Poor Grid Quality Conditions

The foundation for a successful market transformation to solid-state lighting is good product quality. To prevent poor quality lamps from penetrating markets, a number of issues need to be addressed in parallel, including: product specifications adapted to local grid conditions; acceptability of higher pricing for a more durable product; supplier selection process; and procurement mechanisms that allow for testing, monitoring and verification.

Existing standards such as those from the International Electrotechnical Commission (IEC) and IES-NA offer a foundation for ensuring the reliability of solid-state lighting systems in developing countries, and are likely adequate in countries with good electric grid infrastructure, such as China. For those countries with highly unstable grids (e.g., DRC, Nigeria), however, some of the existing requirements, particularly related to testing protocols, may be inadequate to protect grid-connected LED lighting against catastrophic failure. Leveraging existing specifications and harmonizing any additional requirements will limit testing burden and costs for manufacturers and help to create sufficient volumes to attract larger, higher quality manufacturers.

In 2010, the combined African market represented only about 5% of the global lighting market, and African markets remain fragmented, with LED technologies subject to significant import duties in many countries, combined with high inter-African transportation costs. Thus the largest LED manufacturers historically had little incentive to prioritize sub-Saharan African markets. Fortunately, this is changing rapidly, as manufacturers seek to lock-in market share and take advantage of Africa's growth potential. Within the past several years, some manufacturers have begun to develop LED products for specific African markets, such as the EcoBright LED replacement lamp developed by Philips for the Nigerian – and broader African – market, which can handle voltage fluctuations between 48–250V and withstand voltage peaks and transients that result when switching between normal grid and generator electricity sources. 48-250V. Sales are on track to give this one product a 5% share of the LED bulb market, with sales projected to accelerate next year in those countries with a poor grid, due to positive experience on the ground.

There is also a need to address the disparity between the quality metrics for LED devices in the lab and the actual grid and ambient conditions that the technology will encounter in the field (e.g., hot climates, large voltage fluctuations and transients). Additional research is necessary to better define grid performance so that laboratory test can more closely track real-world expectations. Particularly in tropical developing countries, it is crucial that LED devices survive as claimed, or the outcomes (i.e., return on investment, market spoilage) could be negative. The main issues in LED device reliability is the ability of device electronics to handle spikes/valleys in input voltage and the ability of the design to dissipate the heat generated by LEDs and electrical components.

Suitable quality and performance standards can be either mandatory standards issued by standardization bodies and governments or bulk procurement specifications. Some representative, but not inclusive, examples of existing international standards are:

- Standards that describe the chromaticity requirements (ANSI/NEMA C78.377-2011 and IEC 62707-1:2013) and color rendering evaluation (CIE Publication Number 13-3-1995) for LED devices;
- Standards that describe methods to measure lumen maintenance of the LED (IES-LM-80) and luminaire levels (IES-LM-84);
- Standards applicable to voltage surges in low voltage (< 1000 V) AC circuits such as ANSI/IEEE C62.42.1-2002
- Standards applicable to inrush current for electronic drivers such as NEMA 410-2011.
- Standards applicable to product safety such as IEC 62031:2008 and IEC 60598-1:2014.

While these and other international standards for LED products may be directly applicable to regions with a stable, high quality electrical grid, their applicability in regions with less reliable grid networks is unclear. Nonetheless, these standards can serve as a starting point for developing regional standards provided that several precautions are followed including:

- International standards should be supplemented only as needed, and coordinated across countries to the extent possible;
- Supplemental specifications should be designed to work hand-in-hand with an existing international standard (e.g., IEC) to avoid inconsistencies. In Africa, power grids are all 50Hz and 220V – 240V; those with specifications are covered by IEC standards.

The more aligned the specifications are, the greater the incentive manufacturers will have to develop products to meet the demands of developing country markets.

Although IEC standards are required in only a few African countries, IEC standards are always used as reference, and large tenders for bulk purchasing of lamps are usually based on IEC standards. Eskom, for example, created their own Downlighter Lamp Technical Specification for General Lighting Services (applicable to LED products), drawing from IEC draft standards and the IES-NA LM standards to qualify products for their energy efficiency programs. Initially many of the new importers had products with low efficacy, short life and poor colour rendering properties. The electrical power factor is still a problem (with some power factors as low as 0.2), although most have met the minimum power factor of 0.50 for lamps and 0.86 for luminaires. South Africa will adopt the IEC standards with minor local requirements such as supply voltage 230V, 50 Hz.

The common specification for operating voltage for LED lamps is 220-240V, with a tolerance of +/- 10%. This specification is acceptable for stable grids, however not for unstable grids in some African countries like Nigeria and DRC. A critical mass has been lacking to create a common international specification to increase the tolerance to voltage fluctuations and peaks for challenging grid situations. IEC would be the obvious platform to discuss increasing the operating voltage range, however very few African countries play an active role in IEC and hence have voting rights (in part, because of the fees charged), so countries with stable grids dominate IEC's deliberations. A widening in specification of the voltage range can have a large impact on the design of the electronics incorporated in LED lamps and might increase the material costs, so this will be an uphill battle.

B. *Market Oversight and Transparency*

Beyond development of suitable specifications for LED products intended for poor electric grid conditions, there is a pressing need to improve market oversight and transparency. A key government function in lighting market transformation is establishing and enforcing product standards, which involves the standards themselves, a well designed registration (information) system and effective compliance verification mechanisms.

Certified product databases are an important prerequisite. Given the rapid pace of technological change, regional cooperation on quality standards and compliance mechanisms should be complemented by the development of international data standards for reporting energy performance and related product information on SSL lighting. Accurate, comprehensive and up-to-date market intelligence on efficient lighting technologies is generally lacking. Although there have been several studies on developing country lighting markets and assessments of individual country markets, the data basis for SSL is poor, not the least because of the proliferation of new suppliers, as well as the rapid pace of technological change. Consistent data on certified products would pave the way for greater market transparency and provide the market intelligence needed by the private sector to create new business models, by governments to check compliance and design effective market transformation policies, and by consumers to make energy-smart purchasing decisions.

Initial work has been done under the Super-Efficient Equipment & Appliance Deployment initiative, resulting in a system for capturing, updating and maintaining data on individual product models (a global data framework) and a data standard, which defines which fields are required for each product category, how they should be named and what are acceptable values for each [18]. Product specific work on SSL technologies is needed to complement the generic product category definitions already developed.

Countries with timely import statistical information and/or certified product databases would be able to take advantage of new digital compliance-checking approaches. Continuous market surveillance and automated compliance checking is already being piloted in a number of jurisdictions [19]. Yet even in countries with low internet access, a simple telephone app can allow shoppers to validate SSL claims against government databases at the retail point of sale.

C. *LED Market Development Activities*

Ensuring SSL quality and enforcing minimum performance standards are prerequisites, but these government actions must be complemented by market development and innovation strategies to transform global lighting markets. Four pervasive barriers to market transformation persist and inhibit the uptake of LED technologies:

- Lack of awareness and information on quality, use and waste management issues;
- Market entry barriers, in some cases coupled with a lack of acceptance, which restrict product availability locally;
- High implied discount rates, such that end-users demand very short paybacks for what is essentially a capital good;
- High upfront costs relative to alternative technologies on a per lamp basis that cannot be financed.

The promise of long product lifetimes and controllability creates opportunities for new business models and upstream approaches to most effectively address the discount rate and purchase price barriers to LED deployment facing consumers. LED technology deployment can facilitate efforts to reform electricity tariffs, while eliminating power generation subsidies, increasing energy access and advancing other societal goals. Given the right regulatory framework, utilities can play a transformative role.

Under the United Nations Sustainable Energy for All (SE4All) initiative, the United Nations Environment Program (UNEP), with funding from the Global Environment Facility and a growing number of partners, is spearheading the Global Lighting Energy Efficiency Accelerator [20]. The effort seeks to engage 30 countries initially in comprehensive market transformation activities, including establishing regionally harmonized mandatory energy performance standards; developing baseline country lighting assessments; and creating and executing on efficient lighting roadmaps through a variety market development activities. The emphasis will be on leapfrogging to SSL technologies.

The deployment of LED technology could be effectively integrated with efforts to reform the power sector and increase energy access, as well as to advance other societal goals. In August 2014, officials from the South African Development Community and the Southern African Power Pool agreed to support a regional strategy to transition to energy-efficient lighting by 2020. The shift could save the region an estimated US$ 570 million and reduce CO_2 emissions by 9 million tonnes annually [21]. As illustrated above, integrating solid-state lighting into utility business models in countries with financial loss-making grids has great potential to improve electricity supply economics and access to electricity, while reaping multiple other sustainable development benefits.

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