The lights will stay on, but need policy makers to make them shine in the eye of the consumer

Erik Page, Stuart Jeffcott, David Wellington, Steve Beletich, My Ton, Ana Maria Carreno

Abstract

The primary focus of this study was to establish the availability and quality of lamps to replace 25-100W general service incandescent lamps (otherwise known as omni-directional incandescent, or A-line lamps) by examining 25 historical and contemporary data sets of CFL and LED products drawn from developed (Australia, the EU and the USA) and developing economies (Cambodia, Indonesia, Laos, the Philippines, Thailand, and Vietnam). The availability of high quality replacement lamps was confirmed by the study.

Nevertheless, in all markets analyzed, the CFLs and LEDs that were available failed to meet national requirements and/or internationally recognized norms of consumer acceptability, in some cases by substantial margins. However, in some markets these poor performing products were relatively scarce. This protection of the market appears directly related to:

- *A strong policy support framework (MEPS, Labels, Subsidies, etc. as appropriate to local conditions, and*
- *Ongoing and visible market surveillance/check-testing activities.*

The paper investigates these issues and potential solutions (e.g., how cross border sharing of enforcement information may be achieved), along with a range of other interesting outcomes including the inter-relationships of lamp performance parameters.

Introduction

Lighting is responsible for 15% of electricity use around the world and for approximately 6% of total annual global greenhouse gas emissions (UNEP, 2015). To reduce this effect, many governments have phased out the least-efficient lamps. Many more are now working to facilitate a transition to more cost effective, energy efficient lighting options.

For those regulators and countries in the process of, or considering, a, transition to more energy efficient lighting, the use of MEPS (minimum energy performance standards) can be a cost effective option. However, to be effective, MEPS must be carefully applied; performance levels and other requirements must be determined using up-to-date technological developments and market trends for lamps. For some countries and regions, the lack of capabilities or resources to conduct their own baseline studies, track market trends, conduct market surveillance or product testing, can pose a significant barrier to creating market-realistic MEPS. Furthermore, not having access or awareness of available data may result in MEPS that are not reflective of the regional or international trends.[1]

Once a MEPS policy or program has been established, countries need to monitor, evaluate, update and revise their MEPS on a regular basis. Many studies have indicated that the most important factor for program success (along with appropriately set MEPS requirements) is a functioning monitoring, verification, and enforcement (MVE) framework. MVE is critical for both the market data it can collect and the deterrence that it can provide.

The authors of this paper collected an extensive range of international data sets of general service lamps (GSLs), representing 25 historical and contemporary data sets of CFL and LED products that were generated over the past decade, primarily by energy efficient lighting programs around the world.[2] A robust

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[1] The United Nations Environment Programme's en.lighten Initiative has recommended where feasible, national MEPS requirement levels should also take into account regional conditions and international standards. *Developing Minimum Energy Performance Standards for Lighting Products*. UNEP 2015.

[2] This work was supported by CLASP, UNEP, and the Government of Australia. The full report is available at www.clasp.ngo

comparative analysis on product performance was conducted on these data sets, as well as the policy frameworks influencing the penetration of lamps into each market in order to answer the following key questions:

- Which omnidirectional LED and CFL products are available to replace incandescent lamps, and how is this availability changing over time?
- Are these CFL and LED lamps of good quality, and does this quality differ internationally?
- Which governments have performance requirements that apply to CFL and LED lamps, and how do they compare?
- For those economies with regulatory requirements, what are the current levels of compliance and does this differ internationally?

Focus of Study

This study is limited to general service omnidirectional lamps: those that generate light in all directions. These lamps are also known as "A" lamps, and have a medium (E26) screw or bayonet base. The US also has a legal term of "general service lamp." These lamps generally synonymous with the term "light bulb." The CFLs and LEDs in this study are considered direct replacements, and contain all of the necessary parts for operation within the body of the lamp itself. This study does not cover reflector lamps (also called flood lights).[3]

Data Availability, Quality, and Limitations

Overall, approximately one million individual data points have been amassed from a wide variety of both publically available and confidential sources (those who have requested their identities not be disclosed). These sources record the performance of over 10,000 products currently or previously available in the years 2006 - 2014.[4]

Although an enormous amount of analysis is possible with this data, the material presented here is limited to that which is relevant to answering the questions presented earlier. Further, in answering these questions, material presented is primarily related to the analysis of performance parameters generally deemed to be of critical importance to the policymaker and to the consumer experience, i.e., light output, lamp power, efficacy, color rendering index (CRI), lumen maintenance, and lifetime.

These data sets have been sourced from a wide variety of organizations, all of which have unique approaches to product sampling, testing, and data recording, and required a significant effort to integrate into a comprehensive database. These differing approaches affected the comparability of the data and the resulting quality of the analysis, and limited opportunities for direct comparison. In order to present the widest possible comparison of historical and currently available products, from the broadest number of economies, a data quality analysis was also made on the degree of 'reliability and comparability' that can be attributed to the specific data. From this analysis, a two-part *Data Confidence Score* has been assigned to each data set, reflecting:

1. **Data confidence:** Combines data reliability and data source to give a score from 1 to 5. A score of 1 signifies a high level of confidence in the reliability of data and the source and a score of 5 signifies low confidence in one or both.

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[3] SSL and LED both apply to the same set of technology. Throughout this study, when CFL is used it means self-ballasted CFLs.

[4] In assembling this data, acknowledgements are made for the assistance given and data provided by:

- The Australian Government's Department of Industry;
- The Australian Consumers' Association (CHOICE);
- The United Nations Environment Programme-Global Environment Facility (UNEP-GEF) en.lighten Initiative, the Global Efficient Lighting Centre (GELC) and the Governments of Indonesia, Lao PDR, the Philippines, Thailand, and Vietnam);
- The United States Agency for International Development's Eco-Asia program.

2. **Market representativeness:** A score of A is given to data sets that are deemed to be representative of the whole of the relevant market, and B to those that are deemed not to be fully representative.[5]

Product Availability, Quality and Trends

This section examines the quality of CFL and LED lamps, how they evolved over time, and any observable correlations with the regulations of the economies studied. The lamp quality parameters critically important to the consumer in most economies, and for which significant quantities of data are available, are efficacy and CRI and hence these are used as the basis for the analysis. Lumen maintenance and lifetime are clearly also of importance to consumers and regulators but limited contemporary data is available on lumen maintenance, and no datasets contain lifetime except that claimed by manufacturers. Hence, only limited analysis of lumen maintenance is possible with no analysis of product lifetime undertaken.

In order to investigate the availability of equivalent replacement lamps for given wattages, it is first necessary to ascertain how much light is emitted from standard incandescent lamps at the various "standard" lamp wattage thresholds. This is somewhat complicated by the range of lamp outputs on the various markets, and the fact that light output of filament lamps is directly affected by the voltage under which it is tested.[6] However, Table 1 shows the approximate light output for GSLs at both 110V and 230V (drawn from European, which also serve Australia, and North American manufacturer catalogues). The values from this table are then used to directly compare the lumen packages for CFLs and LEDs, rather than claimed equivalence or rated wattages.

Table 1: Approximate light output for general service incandescent lamps in international markets

	European Catalogues				**North American Catalogues**			
GSL Power (tungsten incandescent)	Philips *(lumens)*	GE *(lumens)*	OSRAM *(lumens)*	**Average *(lumens)***	Philips *(lumens)*	GE *(lumens)*	OSRAM *(lumens)*	**Average *(lumens)***
25W	NA	230	220	**225**	220	NA	190	**205**
40W	410	410	415	**412**	500	505	NA	**503**
60W	700	700	710	**703**	880	865	880	**875**
75W	NA	930	935	**933**	1,195	1,190	1,200	**1,195**
100W	1,330	1,330	1,330	**1,333**	1,590	1,710	1,720	**1,673**

Although mapping of the national requirement for lamp performance allows analysis of compliance of products *within* any particular national market for efficacy (but applicable to other performance criteria), it does not provide an adequate absolute framework against which product quality can be benchmarked *across* international markets for a number of reasons including the fact that selection of any individual national performance requirement against which international products are compared is likely to provide a distorted picture of "quality." Fortunately, there are internationally developed performance criteria that are suitable for application in such cross market analysis for both LEDs and

[5] It should be noted that even where a data set is not considered representative of the whole market (e.g., a data set drawn from a premium labeling registration system such as ENERGY STAR in the USA), it may still be comparable with other data sets drawn from similar market segments or for understanding specific segments of that market.

[6] There are a large number of "equivalence" tables used in regulation and other policy measures actions around the world. For example, in the EU, Table 6 of Commission Regulation 244/2009; Section 9.2 of version 1.0 of the US ENERGY STAR product specification for lamps; and from government issued data in Australia available at http://www.energyrating.gov.au/products/lighting/phaseout. There is little alignment between these various equivalence tables partially due to voltage difference, but also local cultural expectations and traditional product availability. Hence, a transparently derived, globally appropriate alternative is proposed.

CFLs: namely the International Energy Agency's 4E SSL Annex's Product Performance Tiers[7] and the performance limits proposed to the IEC for self-ballasted CFLs, supported by Australia and a number of Asian countries.[8] Use of these internationally agreed tiers is helpful as:

- In each case they provide 3 bands of increasing levels of product performance; and
- They are based on international agreement among a range of stakeholders and are not directly aligned with the requirements in any one economy.

Therefore, where international comparison of lamp quality is required as part of the following analysis, the 4E SSL LED and proposed CFL performance tiers will be used as the basis for these comparisons. **However, it should be noted this is *only* for comparative measure of quality and lamps of lower performance tiers should not necessarily be assumed to be inferior as they may well be both compliant with regulations in the market from which they were sampled, and appropriate to local needs in those markets.**

International comparison of CFL quality: Efficacy

Figure 1 shows the measured efficacy of CFLs in 2013 or 2014 from all economies analyzed compared to the requirements of the proposed CFL tiers and relevant national requirements where they exist. As can be seen from these graphics, for **all** economies analyzed there are a very high proportion of lamps that meet the highest efficacy requirement. Further, with the exception of data drawn from the Australian registration system, none of the data sets displayed is fully market representative and therefore there are likely to be additional products that exceed these requirements.[9] Thus, there is clear evidence of the availability of high efficiency CFLs in all markets. Unfortunately, in a number of the markets there are also a notable proportion of lamps tested that fail to meet the lowest proposed CFL requirements (notably 11% of both the Cambodian and EU data sets), and in a few case, national mandatory requirements. Lower efficacy levels were particularly evident at the lower lumen levels (25 and 40W incandescent GSL equivalents), i.e., the lamp sizes used in large numbers in a number of the markets analyzed.

As the vast majority of smaller lumen output lamps within both the Australian and ENERGY STAR data sets achieve the challenging national and the proposed requirements,[10] data suggests that the low lumen, lower efficacy products elsewhere are the result of either less challenging national performance requirements and/or less stringent MVE regimes rather than any technical barrier. Such a conclusion is supported by the very wide spread of efficacies for products across the entire lumen output range. This finding also highlights the potential for the more developed economies to raise the minimum and premium performance requirements of CFLs (or align more with LEDs parameters and performance levels if they exist) in their national programs to maximize the consumer and national energy savings available without jeopardizing product availability across all lumen ranges.[11]

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[7] Refer to http://ssl.iea-4e.org/product-performance. These are currently under review for update.

[8] Note that these CFL performance tiers were proposed as a work item for the IEC (reference 3 4A/1754/NP PNW *34A-1754: Self-ballasted compact fluorescent lamps for general lighting services - Performance limits).* The proposal to adopt the work item was rejected by TC34. Nevertheless, the performance tiers proposed provide a suitable framework for the purposes of this analysis. However, the term "proposed" is used as a preface to each reference to the performance tiers to emphasize the tiers were not adopted by the IEC.

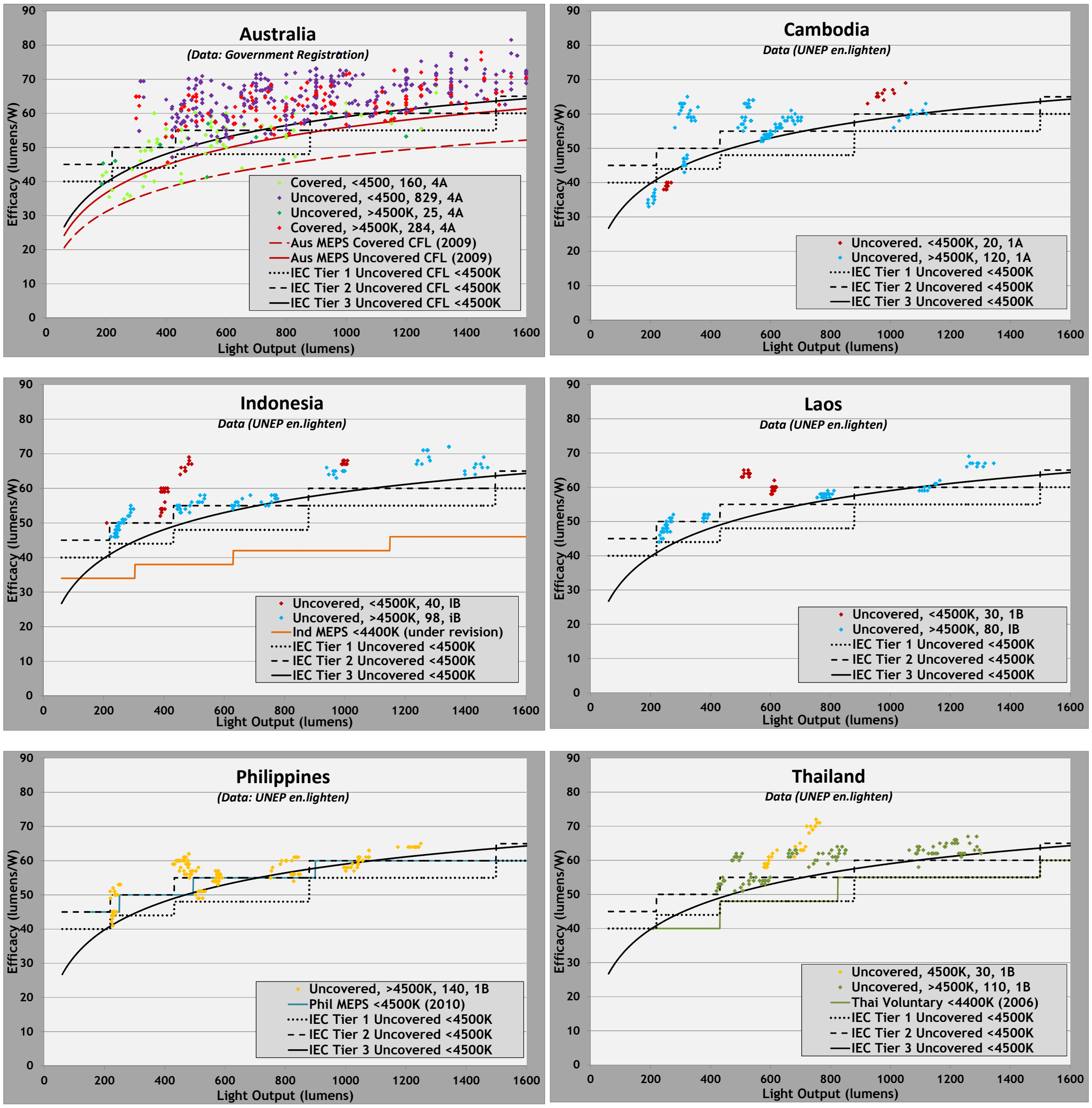
[9] It is unknown whether these high efficiency lamps in the different markets are very similar models with different packaging and/or branding produced by a small number of global suppliers, or whether there is a genuine range of products across all markets.

[10] Note this is to be expected as the Tier 3 requirements closely align with the minimum requirements of both Australian MEPS and ENERGY STAR.

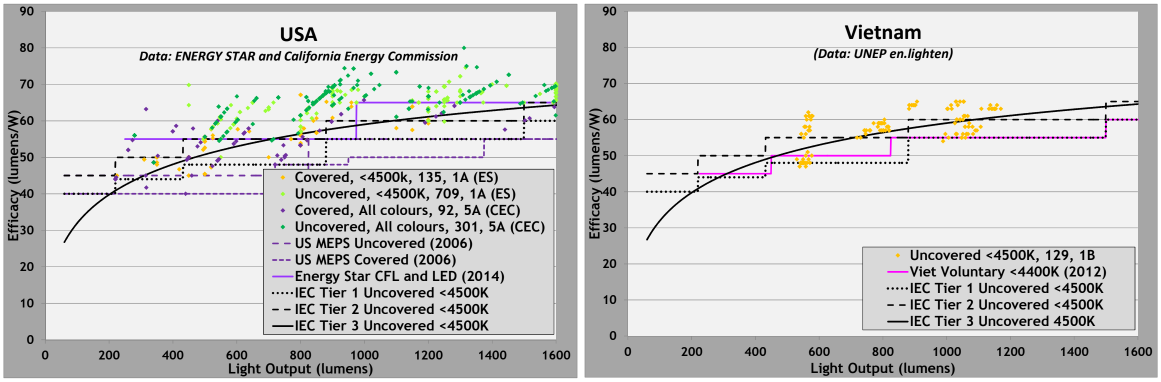
[11] Economies with good CFL MEPS in place and without LED MEPS may consider directing both regulator and industry resources to LEDs in preparation for further price and performance evolution.

Figure 1: Light output and efficacy of CFLs in 2014 data sets from Australia, Cambodia, Indonesia, Lao PDR, Thailand, the USA, and Vietnam compared with proposed CFL Tiers and national regulations

(Data point legend reads: Covered/Uncovered CFL, Color Temperature, Number of Samples, Data Confidence Score. Performance requirement lines show levels of any local performance requirements and those of the IEC Tiers[8,12])



- [12] For clarity and simplicity of presentation, proposed CFL Tiers are only shown for bare lamps with CCT<4,500K. Tiers 1 and Tier 2 efficacy requirements for lamps with CCT>4,500K lamps are slightly more stringent than the Tier 1 and Tier 2 values shown. Efficacy requirements for all covered lamps are less stringent than the values shown.



International comparison of CFL quality: Color Rendering Index (CRI)

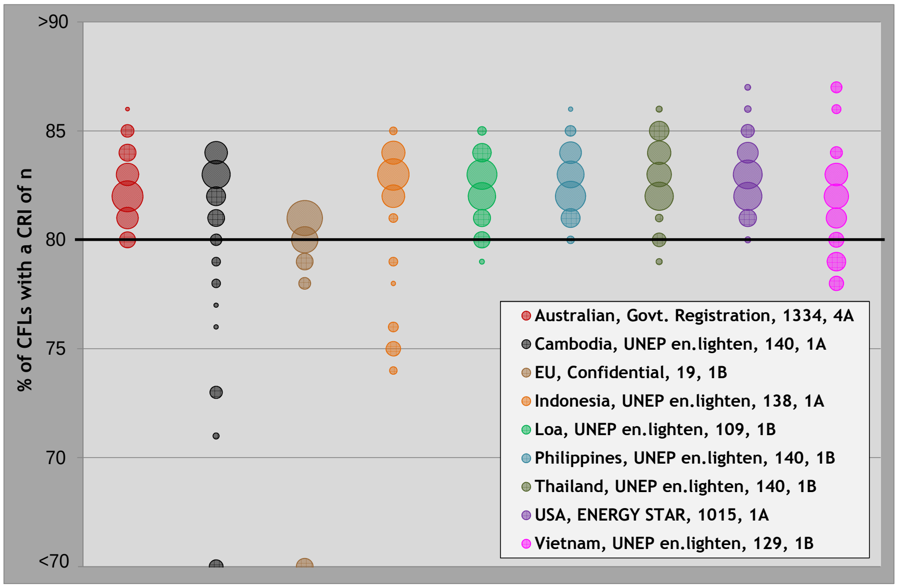
It should be noted that CRI is not universally regulated for CFLs, although this may be a function of lamp color being considered less important than price to the consumer in many economies. Among the economies studied only Australia, the EU, Indonesia, and the USA (within ENERGY STAR) set thresholds for CRI, with these thresholds are universally set at 80. Figure 2 shows the distribution of CFL CRI values around this 80 CRI threshold for all economies studied.[13]

The most important observation is the very high proportion of CFLs that reach the 80 CRI threshold, with or without regulation or program drivers.[14] Further, although it appears CFLs from some economies are performing better than others (e.g., 100% attainment of the threshold in Australia, Philippines and the USA[15]), lamps within almost all economies perform above 78 CRI, which is generally within the test/laboratory tolerance range. However, a few poor results from Indonesia and, again, Cambodia and the EU (both with some tested lamps below 70 CRI), suggest ongoing vigilance of markets is still necessary to counter the entrance of products failing to meet consumer expectations in markets where color is important.

[13] The universal use of a CRI of 80 as acceptable by consumers is evidenced by the proposed IEC performance requirements using a CRI threshold of 80 for all three proposed Tiers.
[14] This may support the hypothesis that a small number of manufacturers supply products to many markets and do not find it economic to reduce lamp specifications where regulations are less challenging.
[15] Again this is partially a function of the data sets selected, in particular the Australian and US ENERGY STAR datasets are drawn from registration systems that require CRI=80 over an average of samples for entrance. However, drawing from the Australian 2013 check testing (data set B), 92% of lamps achieved of exceed the 80 CRI threshold, and significant number of the remaining lamps were within test/laboratory uncertainty ranges of the 80 value.

Figure 2: Distribution of CRI values of CFLs in 2014 data sets from Australia, Cambodia, Indonesia, Lao, Thailand, the USA and Vietnam compared with proposed IEC Tiers and national regulations.

(Legend reads: Country/Data Source, Number of Samples, Data Confidence Score. All Types of CFL included, ie Covered and Uncovered and all color temperatures. Size of circles denotes proportion of lamps in the data set achieving specific CRI values)



International comparison of LED quality: Efficacy

As previously noted, there are relatively few data sets for LEDs, so measurement of market quality is challenging, particularly given the rapid market developments. However, contemporary data sets are available for Australia, the EU and the USA and these are presented for lamp efficacy in Figure 3 in comparison with the 4E SSL Tier requirements, and EU MEPS and US ENERGY STAR regulations.[16]

Again it is not surprising to see the ENERGY STAR registered product compliance at 100% given the data set is drawn from the registration system. Similarly, there is little surprise to see EU products are also compliant with the EU regulations given some of the data sets target premium products. Further, the EU performance requirements were set in 2009 and LED products have progressed significantly over that period.[17] However, there are poor performing products with efficacies below the basic SSL Tier 1 requirement of 50 lm/W shown in other US data sources and in Australia, neither of which have MEPS for LEDs.

Within this context, the very broad spread of efficacies for any given light output within each economy is significant. Lamp efficacies for any given lumen range are widely spread across the entire SSL Tier 1-3 range, with some lamps recording efficacies of over 100 lm/W, far in excess of the highest SSL

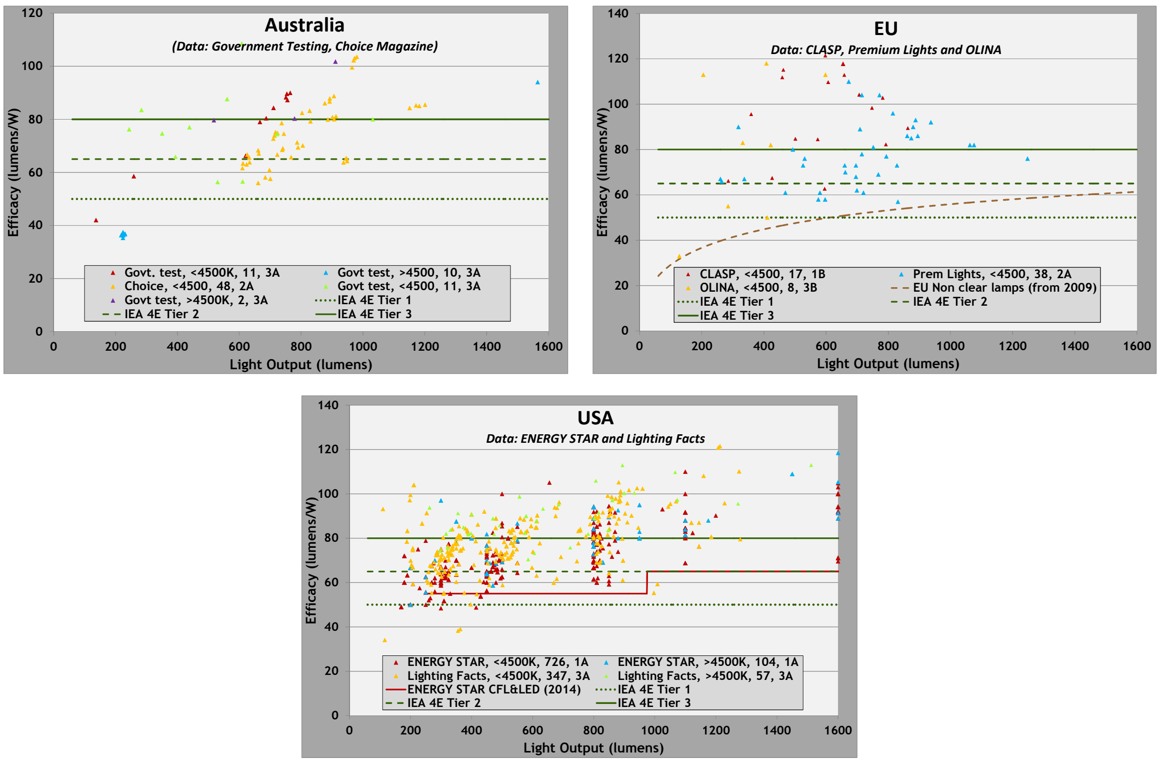
[16] At the time of report preparation Australia has no performance requirements for LEDs but a consultation process is currently underway which may result in MEPS and/or Labeling for LEDs. However, the Australian industry association (Lighting Council of Australia) has a voluntary SSL quality scheme in place. Refer to http://www.lightingcouncil.com.au/site/ssl/overview.php. Similarly, while the USA has a voluntary specification for LEDs in ENERGY STAR, there is now currently a mandatory specification. The USA DOE is currently developing a technology neutral specification for GSLs (i.e. it will apply to both CFLs and LEDs). More information on the USA DOE GSL rulemaking can be found at:
https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=4

[17] As noted previously, the EU non-clear lamp requirement is actually technology neutral and so was not developed for LEDs specifically. Further, at the time of report preparation, the EU is undertaking a study aimed to bring together all lighting regulations and will most likely increase the efficacy (and other) performance requirements for LEDs.

Tier 3 requirement.[18] Thus, while Tier 1 products still provide a basic "quality lamp" to the consumer (50 lm/W is a *relatively* high efficacy compared with the GSL alternatives) there is significant potential for the EU and ENERGY STAR to raise the minimum and premium performance requirements for LEDs to maximize the consumer and national energy saving, again without jeopardizing product availability across all lumen ranges.

Figure 3: Light output and efficacy of LEDs in 2014 data sets from Australia, the EU and the USA compared with 4E SSL Tiers and national regulations

(Data point legend reads: Data Source, Color Temperature, Number of Samples, Data Confidence Score. Performance requirement lines show levels of any local performance requirements and those of the IEA 4E Tiers)



International comparison of LED quality: Color Rendering Index (CRI)

Available data sets for CRI of LEDs[19] are limited to Australia, the EU, and the USA, and these are presented in Figure 4 in comparison with the 4E SSL Tier requirements for CRI, EU MEPS, and the US. ENERGY STAR requirements.[20]

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[18] It is interesting to note that the 4E SSL tiers are all flat lines, i.e., there is an underlying assumption that efficacy is not a function of lumen output for LEDs. However, within the largest contemporary LED data set (amalgamated for all data sets available for LEDs available in the USA in 2014), there is a strong positive relationship between lumen output and efficacy, i.e., as lumen output rises, so does efficacy. However, when broken into smaller lumen ranges, this relationship is much weaker for lamps with 0-500 lumens, and is actually negative for products in the 1,500-2,500 lumen range. Unfortunately, from the data available it is unclear whether this is a reflection of the typically lower efficiency of smaller products resulting from the proportionately greater effect of control electronics, the challenges of dissipating heat from larger lumen lamps designed for standard fittings, and/or other factors.

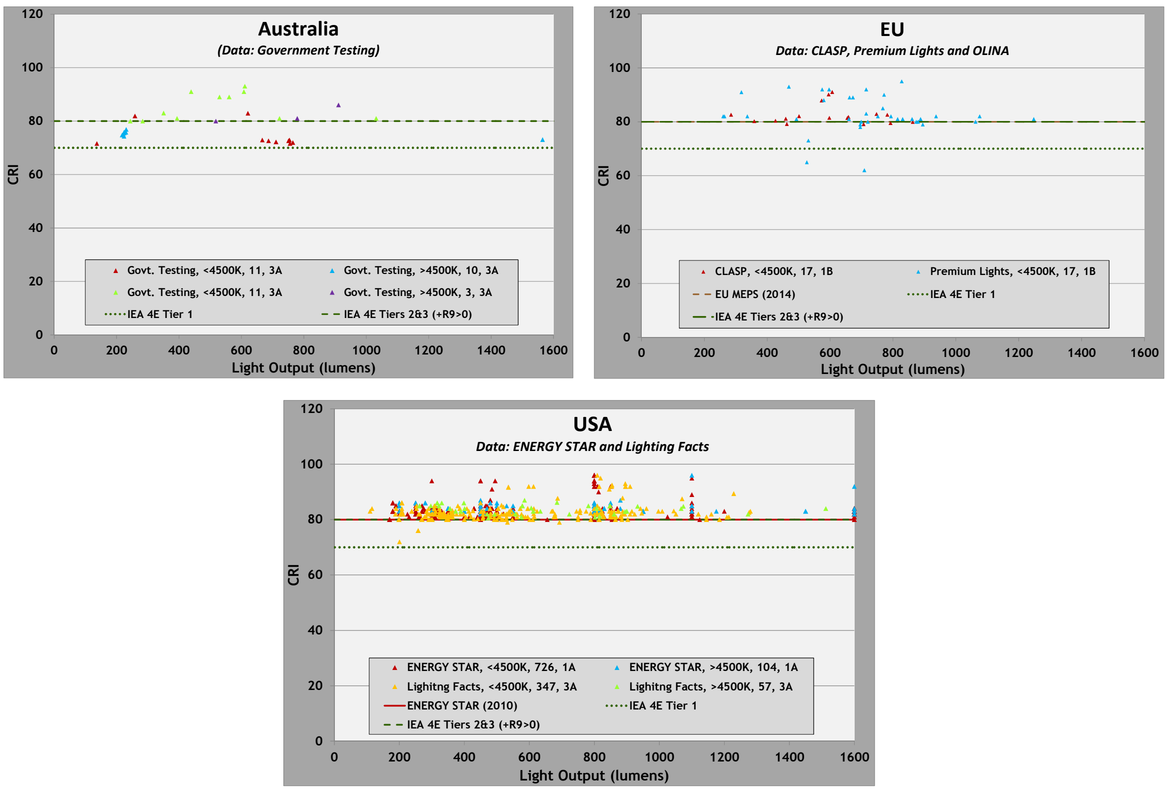
[19] As extensively discussed elsewhere, the use of CRI as a metric for measuring the color performance of LEDs is limited (a clear explanation is provided by US. DOE at http://cool.conservation-us.org/byorg/us-doe/color_rendering_index.pdf). However, while extensive efforts are underway to find alternatives (including the recent publication of TM-30 by the Illuminating Engineering Society), at present CRI remains the typical international measure of color quality of LEDs, a fact reflected in the data available, and so CRI is used in this analysis.

Almost all LED lamps in the USA meet the minimum IEA SSL Tier 3 and ENERGY STAR requirement of CRI>80. This is not the case for a significant proportion of EU lamps where the MEPS threshold is also CRI>80, nor in Australia where there is currently no regulation.

However, again there is a wide range of CRI values in each market, with some lamps exceeding CRI=90. This suggests a CRI>80 is not significantly challenging and may be suitable for serving as an absolute baseline for regulation in all economies to protect the consumer until alternative color characterization approaches are adopted wide-scale within the lighting industry. Nevertheless, once regulations are in place, again the EU data set demonstrates the need for ongoing surveillance activities to protect the market from lower performing products.

Figure 4: CRI of LEDs in 2014 data sets from Australia, the EU and the USA compared with 4E SSL Tiers and national regulations

(Data point legend reads: Data Source, Color Temperature, Number of Samples, Data Confidence Score. Performance requirement lines show levels of any local performance requirements and those of the IEA 4E Tiers)



Interrelationship of performance parameters and associated regulatory requirement

It has been known that there is interdependence between performance parameters for both CFLs and LEDs, i.e., improving one aspect of a lamp's performance can result in a reduction in another. An extensive analysis was conducted investigating correlations between each of the key consumer acceptance parameters available in any data set, i.e., lumen output, efficacy, CRI.[21] Interestingly, the analysis found almost no correlation between any pair of parameters, with the exception of lumen output and efficiency. Even the correlation with efficacy was weak—across a broad range of lumen outputs—with an r^2 value of

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[20] At the time of report preparation Australia has no performance requirements for LEDs. However, a consultation process is currently underway which may result in MEPS and/or Labeling for LEDs.
[21] The full report also detailed results from lumen maintenance and CCT parameters. Ideally lamp lifetime would be included in the list of consumer acceptance parameters. Unfortunately no independently test lifetime data was available.

around 0.4 for both CFLs and LEDs.[22] It appears that although the performance parameters are linked for any given lamp design, a similar change to a lamp employing a different design approach may yield very different results. Consequently, no individual parameter can be considered a proxy by which overall lamp performance can be measured or regulated. *This finding reemphasizes the need for regulators and program managers to ensure a wide range of performance parameters are considered when seeking to deliver consumer satisfaction. They should also undertake adequate and ongoing market monitoring/check testing to confirm products are indeed delivering declared levels of performance and satisfying consumers*.

Conclusions

In all economies studied, CFLs are currently available with light output suitable for replacing incandescent lamps up to and including 75W, based on measured values. Within the developed economies there is also demonstrable availability of 100W GSL equivalent CFLs (based on Table 1). Despite limited demand for 100W replacement lamps in Asian economies from available data, there is sufficient indirect evidence to suggest 100W equivalent lamps are also available in these economies. Further, evidence suggests that a high proportion of these GSL replacement CFLs achieve high levels of efficacy, have good color performance (defined by CRI) and, from the limited data available, exhibit satisfactory levels of lumen maintenance.

Thus, based on the evidence, CFLs that fully meet consumer expectations across all key performance parameters are available for all GSL-equivalent wattages from 25W to 100W in Australia, the EU, the USA, and in *most* Asian markets, with the possible exception of Cambodia. This outcome is not surprising, as evidence suggests CFLs are now a fully mature technology. Further, CFL markets are being widely protected through MEPS in five of the economies examined: Australia, Cambodia, the EU, USA, and Vietnam. Additionally, almost all economies reviewed have extra policy support measures for CFL adoption.

Nevertheless, in all markets analyzed, CFLs were available that failed to meet national requirements and/or internationally recognized norms of consumer acceptability, in some cases by substantial distances. Poor performance on efficacy was more evident among the lower-lumen-output lamps that are in demand in many Asian economies. However, the evidence demonstrates that technically there is no longer a need to accept these lower performing products, and in some markets, for example Australia, they are uncommon.

Key conclusions regarding CFL performance and markets that can be drawn from this analysis are:

- In almost all economies, there is scope to raise current performance requirements for CFLs to further enhance the consumer experience and/or maximize energy savings without significantly limiting the number and range of products available (alternatively, it may be possible to create a technology neutral MEPS, incorporating the characteristics of CFLs and LEDs).
- Most of the developing economies represented (Indonesia, Philippines, Thailand, Vietnam) typically have relatively comprehensive policy frameworks for CFLs, albeit not necessarily as well developed as elsewhere.
- The scarcity of poor quality products appears directly related to the presence of a strong policy support framework, coupled with ongoing and visible market surveillance/check-testing activities.
- In the majority of economies there is a need to strengthen market surveillance, particularly related to the lumen maintenance of products. It is critical to ensure lamps provide extended consumer-satisfying service, and hence remain installed, to yield the appropriate levels of economic and energy benefits.

International alignment of similar national CFL performance requirements offers the opportunity to share information on poor performing products. The inherent benefit is the shared market surveillance costs and resulting higher product quality at the national level. Such an alignment of performance requirements is relatively simple and has been attempted previously, as illustrated by the performance tiers proposed by Australia and a number of Asian countries to the IEC referenced in the report. It is currently being pursued in some areas, for example among Association of South East Asian Nations (ASEAN) members. However,

[22] This relationship is shown in the graphics in Figures 1 and 3 where efficacy generally increases with lumen output, but there are very wide ranges of efficacies for any given lumen output

efforts to internationally align performance requirements should be accelerated and widened. These requirements could increase product quality and lower surveillance costs, and participating economies would benefit from the resulting increased trade and market competition.

The situation for LEDs is more fluid, with very rapidly developing products. In Australia, the EU, and the US (very limited data on LED performance was available for Asian economies), products with sufficient light output to replace all GSLs up to and including 75W have been available for several years. However, significant numbers of LED replacements for the higher lumen output 100W GSL have only recently appeared in the U.S. market. In 2014, there was little evidence that these products had entered the Australia and EU markets. This lack of evidence is at least partly related to limitations on available data and, given the speed of product development, it seems likely 100W replacement products will now have entered most markets.

Of these three developed economies, the EU is the only one that considered all LED performance parameters with its MEPS. It is also the only economy where there is direct evidence that all available LED GSLs could be considered "of at least minimum quality" with respect to efficacy, i.e., performing above 50 lm/W. However, in all three economies, lamp efficacies for any given lumen range are widely spread, with some LEDs now reaching efficacies in excess of 100 lm/W (or roughly 8 times that of incandescent GSLs). Obviously, in those economies where no current MEPS exist, the introduction of similar regulation or other policy support has the potential to rapidly yield high energy savings to the consumer and the overall economy by limiting the penetration of the lower efficacy products that are currently (or are likely to become) available.

Key conclusions regarding LEDs performance and markets that can be drawn from this analysis are:

- There is significant potential for the EU, and the US ENERGY STAR program, to raise the efficacy requirements for LEDs across all lumen ranges to maximize the consumer and national energy saving without jeopardizing product availability.
- Across all three developed economies (Australia, EU, USA), there is evidence to suggest there are possible significant quality issues for color, with some LEDs showing CRI values below 70. However, color quality metrics are being developed, and more analysis using multiple metrics as well as data on preference for metrics is necessary to accurately characterize color quality.
- Lumen maintenance for LEDs is potentially an issue, with results for some products achieving little more than 70% of their initial lumen output at 2,000 hours. This is significantly lower than the lumen maintenance requirements for CFLs in most economies and far below requirements for LEDs, where regulations exist.

Given that long lifetimes and the resulting economic benefits to consumers are key selling points used by policymakers to promote the adoption of high-efficiency lamps, the presence in the market of LEDs with poor CRI and lumen maintenance ultimately risks the slowing of overall market adoption of LEDs (as was the experience of early CFL programs).

The existence of an extensive range of ENERGY STAR qualified products demonstrates that LEDs are available that meet consumer expectations of quality across all key performance parameters. There is a strong expectation among the majority of policymakers worldwide that LEDs will soon penetrate all markets in significant quantities. Policymakers view LEDs as one of the primary products facilitating the transition to lower lighting energy consumption. It is critical to expand availability of high-quality products and protect markets from low-quality products.

Thus, there is an urgent need in almost all economies to develop strong policy frameworks similar to those in place for CFLs (test methods, MEPS, premium product labeling, product registries, etc.) and to rigorously enforce compliance with those frameworks. However, the rapid development of LEDs makes the development of performance requirements on which such frameworks are based challenging (and expensive) to undertake at the national level, as is maintaining effective market supervision of the rapidly changing product landscape. Therefore the potential for international cooperation and alignment of performance requirements highlighted above is particularly important, e.g., through widespread adoption of the 4E SSL performance tiers or a voluntary performance label such as ENERGY STAR.