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Lighting, Energy, Environmental Impacts and Associated Regulations

Michael Scholand LC, Nils Borg, Peter Bennich PhD, and Prof. Georges Zissis, *Fellow, IEEE*

Abstract: Over the past 20 years, the development and adoption of solid state lighting (SSL) has led to substantial improvements in the quality and efficiency of lighting. This disruptive technology enabled a decoupling of lighting and energy consumption, such that global lighting service has increased while associated energy consumption and greenhouse gas emissions have decreased.

Substantial energy savings are still available in the lighting sector through (1) further improvements in LED efficacy, (2) widespread adoption of smart lighting systems and controls, and (3) luminaires designed for circularity. To help ensure that these additional energy savings are captured, a joint effort to develop an international lighting technology roadmap is being launched by the IEEE Smart Lighting program, the IEA 4E SSLC Platform and the International Solid-State Lighting Alliance (ISA). This paper discusses the context for this work, describes the scope of this roadmap and highlights some of the major challenges that will be faced by the lighting industry as it develops the full potential for SSL in the coming decades. This paper also provides an overview of the new work planned by the IEA 4E SSLC Platform, which will, in part, help to address some of those major challenges.

Index Terms—Solid State Lighting, Global Lighting Energy Consumption, Circular Economy, Energy Savings Potential of Lighting, Smart Lighting Systems, Lighting Controls, IEA 4E SSLC Platform

I. INTRODUCTION

Lighting makes a significant positive contribution to our quality of life. Artificial illumination extends our days, enabling us to enjoy spending time with family and friends, and to work in buildings, offices, and factories where there is no natural light. This provision of light however, consumes energy and resources, including both the manufacturing of the luminaire or light source, and the operation of lighting equipment. As our global economies grow and populations expand, there is an increasing demand for lighting services. A recent study found that artificial light consumes approximately 16.5% of the world's electricity production (Zissis et al., 2021); and experts predict that this percentage of electricity used for lighting will decrease as more efficacious solid state lighting (SSL) sources penetrate the market, along with expanded use of lighting systems and controls.

After decades of domination by a handful of large global players, a transformation was ignited in the lighting industry approximately two decades ago through the introduction of solid state lighting (SSL). This disruptive, new technology blurred traditional market boundaries between luminaires and light sources, and enabled many new companies to enter the market. Today, there are thousands of companies working to improve the quality and affordability of lighting around the world, supplying the equipment needed to meet our ever-expanding global appetite for light.

At present, SSL is the best way to transform electrons into photons, using light sources that are highly efficacious, have ultra-long life, and are far more easily controlled than traditional fluorescent or arc-based lamps. Since its introduction two decades ago, SSL has gradually penetrated all end-use lighting sectors and applications, and can be found today in automobile headlights and taillights, household lighting, office lighting, stadium flood lighting, roadway lighting, and much, much more. According to an international market research firm, the global LED lighting market is projected to grow from US\$ 78.9 billion in 2024 to US\$118.4 billion by 2029 – approximately 8.5% combined annual growth rate over the next five years. (MarketsandMarkets, 2024).

In the context of this rapidly expanding growth, new business models and continuously improving lighting technologies entering the market, governments are actively working to establish regulations that work to protect consumers and the environment, to promote quality lighting and sustainable business practices and products. Individual countries or regions can take local action, such as adopting policies that mandate performance requirements and labelling, but today lighting products are manufactured and sold on a global basis, and thus product quality requirements in one economy are likely to effect quality in other, neighboring markets. In this context, the International Energy Agency's (IEA) 4E Implementing Agreement decided to create an Annex focused on SSL in 2010. In recognizing that SSL would revolutionize the lighting market through the introduction of highly energy-efficient, longer-lasting, versatile light sources, including high-quality white light, the governments of the IEA 4E created an entity where participating governments could share SSL research, test data, best practices, policies and programs.

Now entering its fourth five-year term (i.e., 2024-2029), the SSLC Platform is continuing its important work, seeking to support governments in policy making, decarbonization and energy security by investigating, analyzing and defining sustainable, appropriate and adaptive lighting systems that emphasize health, performance, circular economy and sufficiency. The goal of these actions is to integrate the best available technologies into high-quality, energy and resource-efficient lighting solutions.

II. GLOBAL ROUND-UP

The flexibility and efficiency of solid-state light sources enabled a rapid expansion of lighting services over the last 20 years, increasing by over 75% from approximately 135 petalumen-hours of delivered light in 2005 to around 240 petalumen-hours in 2024 (Bardsley, 2024). This lighting service provision took place against a backdrop of decreasing electricity consumption for lighting, reducing from approximately 18% of global consumption in 2005 to around 12% in 2024 (Bardsley, 2024). And while everyone expects the demand for lighting services to continue to increase as the global population expands, economies grow and our living conditions improve, it has become clear that the energy consumption and environmental impacts associated with illuminating our living spaces does not have to increase.

The overall goal is to reduce lighting's share of global electricity use to 7% or less while simultaneously delivering high-quality lighting to many more people around the world. If this objective can be achieved, it will contribute to significant savings on electricity bills, reduce greenhouse gas emissions and alleviate pressure on the electrical grid, freeing up capacity for other important applications such as transportation and building comfort controls.

Governments around the world recognize the pivotal role that SSL is playing and are responding with initiatives and programs that support and encourage the development of improved SSL sources and systems. The following text discusses the markets and R&D programs present in a few key economies for SSL around the world.

China: The China Solid-State Lighting Alliance (CSA) publishes valuable information on the status of SSL technology and markets through its annual reports and presentations to various conferences and meetings, including the BRICS Working Group of the International SSL Alliance (ISA). The CSA reports that annual production of chips and epitaxy increased slightly in 2023 to 30 billion yuan (US\$4.2 billion). CSA also reports that research is continuing into silicon-based yellow SSL emitters and that the efficacy has reached 29%. Revenues from packaging were 78 billion yuan (US\$11 billion), down about 20% from its peak year, 2018. The number of SSL packaging companies in China have gone through a consolidation period, reducing from over 1400 businesses to around 200 in 2024. Overall sales of SSL-based products have

decreased due to very competitive pricing, to 550 billion yuan (US\$76 billion), of which general lighting constitutes approximately half, 250 billion yuan (US\$35 billion). Price pressures on SSL products are increasing, with leading suppliers searching for niche applications and product offerings that could enable maintenance of higher profit margins. Looking to the future, CSA has embarked on four technology roadmaps, covering (1) the solid state lighting industry (2) ultraviolet LEDs, (3) micro-LEDs, and (4) wide-band-gap semiconductor materials technology.

Europe: The European lighting association, LightingEurope, recently published a roadmap called "LightingEurope Strategy 2030" which focuses on promoting awareness of the value of lighting and ensuring a fair marketplace with appropriate regulations and market surveillance. Although the Strategy acknowledges the importance of European leadership in technology and sustainability, no specific goals are quantified or stated. Europe is a global leader in setting quality and performance requirements and labelling of lighting products through the Ecodesign Directive and Energy Labelling Directive, respectively. Europe is now turning its collective attention to applying circular economy principles to its lighting market, including having serviceable and easily recyclable luminaires and light sources. Unfortunately, government funding of research and development in the lighting sector has almost completely disappeared. For example, funding of lighting projects within the European Commission's flagship Horizon R&D program has been reduced by more than 90%.

India: Due to the rapid growth of its economy and the continued reliance on coal in electricity production, India's economic growth is challenging the goal of protecting the planet's climate. India has, therefore, launched programmes such as the government-sponsored UJALA project initiated in 2015 which resulted in the direct distribution of over 400 million LED lamps and 13 million LED streetlights over the last decade. This success stimulated the domestic lighting industry to convert almost entirely to SSL production with sales of 350 billion rupees (US\$4.2 billion) in 2023. In their national roadmap titled 'Vision 2024', India's lighting association ELCOMA, set out that a major goal was to raise the domestic proportion of value-added to SSL products to 70% (ELCOMA, 2021). Vision 2024 also called for building up a strong capacity for exports, to balance out the continued importation of LED chips from China (ELCOMA, 2021). Experts are now working on the new roadmap for India, Vision 2030, and in that document they are raising the target for domestic added value of SSL products to 80%.

Indonesia: A roadmap entitled "Roadmap of Development of High-Efficiency Lightings For Indonesia" was published in November 2021 as part of the ADLIGHT project, a joint venture of the Indonesian Ministry of Energy and Mineral Resources and the United Nations (Indra Irsyad et al., 2021). The report contains a comprehensive analysis of the lighting market in which domestic production was only 12%. The roadmap provides a detailed strategy to accelerate market adoption of SSL, strengthen the domestic industry, reduce

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electricity consumption and eliminate lighting products such as fluorescent lamps which contain mercury.

USA: After more than 20 years and hundreds of millions of dollars of targeted support for building a strong SSL industry in the United States, the Department of Energy has now cut back on its lighting research and development programs. DOE's latest roadmaps on SSL technology and manufacturing were published in 2022 (USDOE, 2022a; USDOE, 2022b). These documents note the continued reliance on phosphors for spectral control and advocate for more research on the development of efficient green and amber emitters and opportunities for color mixing techniques that allow for differential aging of the chips. The need for better control of the temporal and spatial distribution of delivered light is also stressed. In the USA, the national L-prize program is entering its third phase, with applications for manufacturing projects due in 2025 (USDOE, 2024).

III. ON-GOING AREAS OF RESEARCH

While the levels of investment from governments are not as large as they have been in the past, they still play an important role in supporting and encouraging the developing of more efficient, better quality light sources and systems. In this section of the paper, we look across some of the national and regional roadmaps and highlight key research areas which are potentially of common interest to whole industry.

- **Sources:** Raising the efficacy of LED emitters across the visible spectrum to that of blue LEDs, and supporting work to promote implementation of color mixing solutions, would enable the production of white LEDs that offer an efficacy of over 300 lumens per watt. This would mean that an old 60W incandescent light source would be replaced by a 2.7 Watt LED bulb that would likely last 50 times longer. Raising the LED efficacy at high current densities would lower the cost of SSL systems while also saving energy.
- **Optics:** Further advances in micro-optics are needed to help create the desired illumination pattern and minimize stray light, delivering light to where it is needed and will provide the best performance for the end-user.
- **Manufacturing:** In the production lines, greater control of epitaxy is needed to raise the average performance of LEDs. Developing manufacturing facilities close to the user will reduce the cost and environmental impact of shipping, while supporting local economies through new jobs and reduced import costs.
- **Controls, sensors and communications:** Adoption of controls has been slow, and as a result, end-users are not benefiting from the full technical capabilities of

SSL. Improvements in the effectiveness of sensors, standardization of communication protocols and reductions in system complexity are all needed to encourage acceptance.

- **Health Impacts:** More research is needed to understand the impact of light on people of all ages. Research is needed to understand photobiological safety and glare, temporal light modulation, and the effects of circadian, acute neuro-behavioural and long-term effects of artificial light. Research is needed across population age groups, from myopia in schoolchildren to circadian effects in senior housing.
- **Food Production:** Indoor production of food is increasing to combat the impact of climate change on outdoor farming. Optimization of the lighting used to stimulate growth in plants and animals is essential to increasing yields and minimizing the energy needed to produce the light.
- **Sustainability:** Greater use of recyclable materials and design for easy disassembly for maintenance and recycling are critical for sustainability. Increasing SSL lifetimes by better LED design and improved thermal management will also contribute substantially to improving the useful life of light sources and systems.

IV. EUROPEAN POLICY FOCUS

European product policy leads the world in terms of promoting quality, sustainability, and principles of circular economy. Within the next year, the European Commission will initiate a review of its regulations on lighting equipment (EC, 2019a; EC, 2019b) with a view to developing new, updated requirements.

In this section, we highlight four key policy mechanisms that will be taken into consideration in this upcoming review of the lighting regulations and labelling requirements in Europe.

- The **Ecodesign Directive** (2009/125/EC). The Ecodesign and Energy Labelling Working Plan 2022-2024 and specifically the horizontal aspect of recycled content and of scarce, environmentally relevant and critical raw materials, including the technical study behind the Working Plan (Preparatory study for the Ecodesign and Energy Labelling Working Plan 2020-2024). The Ecodesign Directive requires product manufacturers to improve the environmental performance of their products by meeting minimum energy efficiency requirements, as well as other environmental requirements such as water consumption, emission levels or minimum durability of certain components.
- The **Energy Labelling Framework Regulation** ((EU) 2017/1369). The Energy Labelling Regulation

complements Ecodesign by enabling end-users to identify the better-performing products, via the well-known A-G/green-to-red labelling grading.

- The **Circular Economy Action Plan** (December 2015 and March 2020) (CEAP). The Circular Economy Action Plan targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented, and the resources used are kept in the EU economy for as long as possible. It announces a sustainable product policy legislative initiative to make products fit for a climate neutral, resource efficient and circular economy, reduce waste and ensure that the performance of frontrunners in sustainability progressively becomes the norm.
- The **Sustainable Products Initiative** (SPI) and the proposal on Ecodesign for Sustainable Products Regulation. The aim of the SPI is to revise the Ecodesign Directive to set out the EU policy framework necessary to achieve the CEAP objectives. The initiative will also address the presence of harmful chemicals in products such as electronics and ICT equipment. A proposal for Ecodesign for Sustainable Products Regulation has been published by the Commission on 30 March 2022.

V. IEA 4E SSLC PLATFORM

The IEA 4E SSLC Platform was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to implement quality assurance programs for SSL (SSLC Platform, 2024). This international collaboration currently consists of seven members, including the governments of Australia, Denmark, France, the Republic of Korea, Sweden, the United Kingdom and most recently, the European Commission. Now in our fourth term, the SSLC Platform has designed a workplan for the SSLC Platform with activities that fall into the following three key focus areas, all of which are principally focused around lighting systems and controls.

I. Market Assessment and Benchmarking – Smart lighting, sensors, controls and lighting system solutions are becoming increasingly common in today's lighting market, particularly in the professional sector and affluent domestic sector. Smart lighting allows end-users to benefit from improved control of lighting products which also provide energy savings potential, within the right policy context. However, controls may also lead to higher energy use if not applied correctly. In order to better understand smart lighting features and their associated energy use, the SSLC Platform with the inclusion of lighting systems, will continue monitoring and assessing the energy performance plus functionality of smart wireless lamps and luminaires to understand the drivers behind changes in technologies and markets.

- Task 1. Lighting Product Database and Performance Tracker
- Task 2. Smart Lighting: Testing, Controls and Systems
- Task 3. Technology Roadmap Development

II. Understanding Impacts of Lighting – the SSLC Platform will study both the positive and negative impacts of light and lighting systems on people, their health and the environment. This focus area will include an assessment of impacts such as a literature review on light emissions and their impact on people and the environment, as well as looking at approaches for mitigating any negative impacts through the use of smart systems and controls. The task will look into ways to incorporate resource efficiency into lighting, and it will evaluate opportunities and solutions suitable for government-led mechanisms for discrete areas such as dark sky environments and life cycle assessments (LCA).

- Task 4. Lighting and Health Impacts
- Task 5. Energy, Material and Environmental Impacts

III. Support for Standards and Regulations – The SSLC Platform will maintain its quality and performance requirements, providing analysis, metrics and recommended levels that promote harmonized policy measures – both mandatory and voluntary - on SSL market transformation programs around the world. Additionally, this Focus Area will seek to support, engage and encourage communication between the Experts in more of the international standardization activities, specifically that of the key lighting technical committees of the IEC and the CIE. This work will enable governments to more closely follow the standards development process and discuss important revisions to various lighting test methods – including for example several new working groups looking at lighting systems and controls. Finally, this focus area will continue the legacy of support for improving the accuracy of light source metrology, with a fourth international interlaboratory comparison.

- Task 6. Recommended Quality and Performance Requirements
- Task 7. Interlaboratory Comparison
- Task 8. Support for International Standards, Metrics and Measurements

The tasks that are proposed under each of these three focus areas of interest illustrate how the SSLC Platform Management Committee has designed the policy-driven research that it proposes to undertake in the Fourth Term. Complementing these tasks, the Platform Manager will coordinate a concerted effort to communicate and inform key stakeholders about the Fourth Term work. Key target audiences for the SSLC Platform work includes: governments, policymakers, regulators, standardization bodies, test labs, lighting associations, businesses and more. The Platform will thus continue to arrange seminars in the member countries, public webinars and place all news, reports, etc. on the website as well as 4E social media channels.

VI. CONCLUSIONS

There is room for substantial further progress in reducing the energy used to light our offices and buildings, reducing consumption from around 12% of global electricity today to approximately 7% in the future. The increased use of more efficacious light sources, lighting design and smart systems and controls will all play a role in helping to realize these energy savings while at the same time increasing lighting service and quality. The whole lighting community is invited to engage with the IEEE, ISA and IEA 4E SSLC Platform to support the development of an international roadmap to guide this process and help ensure that we all achieve a more sustainable, healthier and better lighting future.

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Michael Scholand, based in London, UK, has an M.Sc. in Civil and Environmental Engineering and has over 25 years experience working as a subject matter expert on products and appliances, supporting energy-efficiency and sustainability. His work includes supporting the public and private sectors to design and deliver policies and programs including test

standards, regulations, energy labelling, voluntary programs, product databases, market surveillance, and more. Michael’s professional skills and experience include supporting European schemes such as ecodesign, Energy Labelling, Restriction of Hazardous Substances, Green Public Procurement, Ecolabel, Code of Conduct and CEN/CENELEC standardization. Michael has worked cooperatively with governments, including as part of the UN Minamata Convention and the UNEP en.lighten initiative. He is Lighting Certified (LC) with the National Council on Qualifications for the Lighting Professions since 2006.



Nils Borg, based in Stockholm, Sweden, is currently the Manager of the IEA 4E SSLC Platform. He is also the Executive Director of eceee - European Council for an Energy Efficient Economy and the Director and owner of Borg & Co AB, a consulting firm specialized in Energy

efficiency policy and analysis. Current projects on behalf of Borg & Co are a number of EU-supported research and market development projects under the Horizon 2020 program on the multiple benefits of energy efficiency (www.m-benefits.eu) and on innovative financing for industrial low-temperature process heat from solar and biomass combined with efficiency investments (www.trust-ee.eu). Nils has a broad intercultural experience from having lived for over a year in Japanese family after high school. As a professional, the work has always focused on international issues, and there is experience from IEA and EU projects, as well as from working as a consultant to Chinese organizations. Nils has a very creative mind and is an interdisciplinary thinker.



Peter Bennich, based in Stockholm, Sweden, is currently a Senior Policy Advisor at Swedish Energy Agency. Peter received his PhD degree in physics at the University of Uppsala, Sweden, in 1996. After two years working as lecturer in electronics and optics, he moved to the Royal Institute of Technology, Stockholm, where he worked as program manager,

overseeing projects on Distributed generation and Power electronic based components in the electrical grid. Since 2002, Dr Bennich has been working with energy policies within the Swedish government, focusing on energy efficiency. In his present position as senior adviser at the Swedish Energy Agency, he is working with the EU product regulations on ecodesign (minimum energy performance standards) and energy labelling. In particular, he is covering the work on the lighting regulations.



Georges Zissis (Fellow, IEEE) Distinguish Professor Toulouse III University, vice-dean Faculty of Science and Engineering. He has been graduated in 1986 from Physics department of University of Crete, Greece in general physics. He got his MSc and PhD in Plasma Science in 1987 and 1990 respectively from Toulouse III

University, France. His primary area of work is in the field of Science and Technology of Lighting Systems. He is director of “Light & Matter” research group of LAPLACE laboratory, in Toulouse, that enrolls 20 researchers.

Prof. Zissis won in December 2006 the 1st Award of the International Electrotechnical Committee Centenary Challenge for his work on normalization for urban lighting systems. In 2009, he won the Energy Globe Award for France and in 2022 he got the Alfred Monnier Award from the French Illuminating Engineering Society. Prof. Zissis was President of IEEE Industrial Applications Society for 2019-20. Today, he is Chairman of IEEE Smart Cities Technical Community and he is chairing the IEEE Smart Lighting Initiative under IEEE Future Directions.