Protection of Dark-Sky Areas in the United States Through Development and Implementation of Warm-Light LED Fixtures

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Executive Summary: The light-emitting-diode (LED) revolution has drastically decreased the quality of the United States' night sky. LEDs are brighter than the sodium doublet lighting fixtures they are replacing, causing an increase in light pollution. Emerging technology promises to replace high-color-temperature LED lighting with lower-color-temperature lighting that reduces light pollution. High-color-temperature, or "cool-lighting" causes unnecessary amounts of light pollution that decreases humanity's connection with the cosmos through stargazing. Policy implementations can increase public awareness of how LEDs affect light pollution through research grants and tax incentive structures. The federal government can directly decrease the United States' luminous footprint by funding research on warm-light LED development , regulating LED lighting on federal projects to only use low-color-temperature LED fixtures and offering incentives to communities to reduce their light pollution through the tax code.

I. Introduction and Background

The night sky has been an inspiration for humanity since the beginning of civilization. Recently, the quality of the United States' night sky has been diminished due to artificial illumination. Light pollution is typically measured by the artificial night sky brightness, which is the integral of artificial light scattered along an observer's line of sight (Cinzano 2014). In the United States, communities can expect between 0-20% increase in artificial night sky brightness per year, depending on geographical region (Holker et al. 2010). Light pollution adversely effects nocturnal creatures and human psychology. Common levels of urban lighting are enough to elevate blood pressure by eight points, and disrupt the human circadian rhythm (Rajkhowa 2012).

Since 2001, the International Dark-Sky Association (IDA) has acted as the chief authority on preserving dark-sky locations across the U.S. As a grassroots organization, the IDA relies on community members to advocate for, lobby for, and maintain dark-sky places. The IDA's designation program provides an international standard for a dark-sky protected area, which include measurements of a communities artificial illumination footprint and community engagement in dark sky preservation (*International Dark-Sky Place Standards* 2022). The IDA designation program has labeled 195 communities, parks, reserves, and sanctuaries worldwide, indicating the quality of dark-sky places to stargazers. The Valles Caldera in New Mexico, and the Katahdin Woods in Maine exemplify IDA-guarded locations within the U.S. (International Dark-Sky Association 2022).

Light-emitting diodes (LEDs) are cheap, efficient lighting tools that have emerged as the dominant artificial light source since 2019. The LED world market penetration rates have increased from 1% of world lighting sales in 2011 to 46.5% in 2019. Projections show 87.4% of consumed light fixtures by 2030 will be LED (Zissis et al. 2021). These forms of light are superior to fluorescent lighting in luminous efficacy and lifespan. The blackbody ratings of LEDs, or the "color temperature", is the temperature associated with the peak of the wavelength distribution. The most efficient LEDs currently have color temperatures ranging from

3000-5000 Kelvin (K), quantifying the light of these LEDs as white or cool (Holker et al. 2010).

White light LEDs are harmful to the nighttime environment for multiple reasons. The high color temperature of LEDs significantly increases light pollution. Rayleigh scattering, the mechanism that produces light pollution, is wavelength dependent. Higher energy (lower wavelength) "bluer light" scatters more than lower energy (higher wavelength) "redder light." LEDs, in general, produce more of this higher-energy light resulting in more light pollution due to Rayleigh scattering (Pena-Garcia & Sedziwy 2020). Due to the low price and energy efficiency of LEDs, consumers tend to install more LED lighting fixtures than necessary. This rebounding effect also increases our nation's luminous footprint by adding superfluous lighting to communities (Schulte-Romer et al. 2019). Modeling has quantified the effects of LEDs on light pollution in cities. Modeling studies have shown a direct correlation between the color temperature a city uses for its lighting and the quality of its night sky (Figure 1; Lamphar et al. 2022).

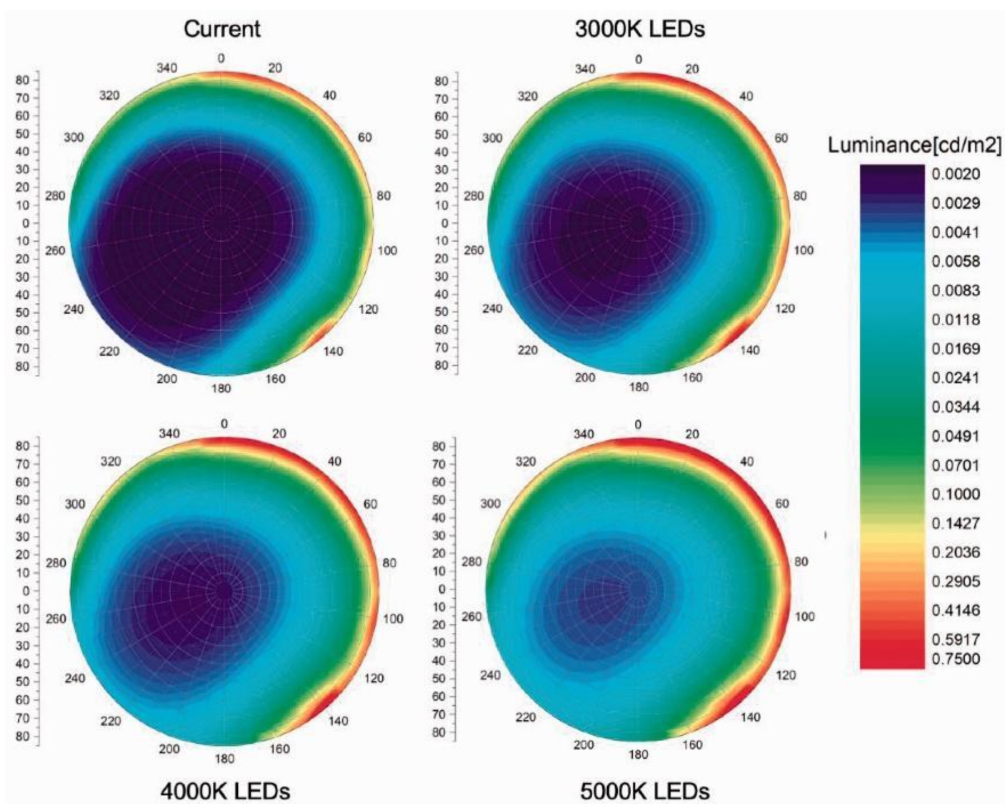

Figure 1: Results of simulations at the location of Reserva Ecológica del Pedregal de San Ángel. These simulations show all-sky imagery simulations if all artificial illumination were at specific correlated color temperatures. The plots are in polar coordinates. The radial dimension ranges from 90 degrees at the horizon to 0 degrees at the zenith, the spot directly overhead. The azimuthal dimension displays true North at 0 degrees. The color grading quantifies the artificial illumination in luminance. The higher luminance – shown as a redder color – indicates more light pollution. The plots show greater luminance as the color-temperature of the modeled LEDs increases, with higher luminance in the 5000K LED model as compared to the 4000K, 3000K, and current models (Lamphar et al., 2022).

II. Analysis

Policies implemented to safeguard United States dark-sky areas are largely at the state and local levels. Attempts to influence policy on the federal level have, to this point, remained unimplemented. State-level dark-sky policy varies by state, with some policy implementations being robust, while others are non-existent. Additionally, research and development are producing lower color temperature LEDs that could rival the efficiency of cool LEDs by 2025 (Pattison et al. 2018). Warm-light LEDs experience a 22% inefficiency due to the current 100 nm wide red phosphor emission linewidth, which causes spillover of light into deep red wavelengths

(Pattison et al. 2018). Warm-light LEDs will have comparable efficacy to white light LEDs once the red phosphor linewidth is reduced to 35 nm. (ibid).

The federal response to light pollution is non-existent. There are no mandates for use of conservative exterior lighting at federal installations. The Department of the Interior manages light pollution within national parks but has no influence over light-pollution caused by surrounding cities. In 2020, the IDA posed an executive order under the Biden administration to audit federal installations for superfluous lighting, and mandate low power, shielded fixtures be used (Hartley 2020). However, the executive branch has not yet acted on this proposed executive order.

State legislation has implemented dark-sky policy to varying effect. For example, New Mexico's aggressive *Night Sky Protection Act* mandates shielding for high power light sources. New Mexico also prohibits lighting of recreational facilities after 11:00pm (New Mexico Statutes - Night Sky Protection 2006). New York conversely uses less assertive legislation, prohibiting the state installation of unshielded light fixtures, to promote long-term change as lighting fixtures are replaced over time (New York - Lighting Restrictions 2015). In contrast, 33 states do not have any dark-sky legislation.

New advances in LED technology produced warm-light alternatives that closely rival the efficiency of conventional cooler-light LEDs. Warm-light LEDs are currently inferior to cool-light LEDs in life span and luminous efficacy. Warm-light LED has half the 50,000-hour lifespan of white light LED. The luminous efficacy of warm-light LEDs is 15% less than cool-light LEDs. (Pattison et al. 2018). However, predictions show that warm-light LEDs will rival cool-light LEDs in efficiency and lifespan by 2025 (Figure 2; Pattison et al. 2018).

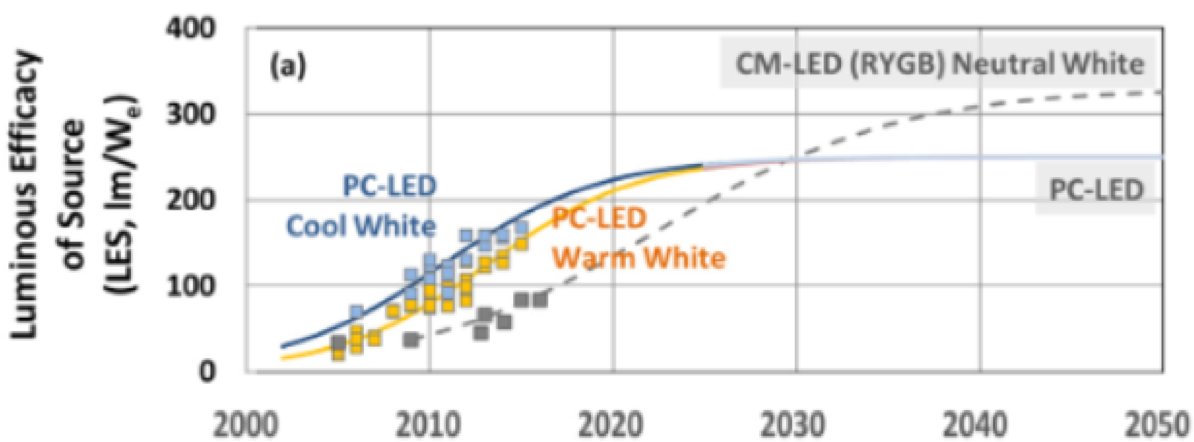

Figure 2: Efficacies of Commercial LED Packages Measured at 25 C and 35 A/cm^2 input current density. The top graph (a) compares the efficacy projections of separate LED light fixtures: Blue = 5700K cool light; orange = 3000K warm light; future prospects for RYGB cm-LED are shown as the dashed gray curve. The top graph shows the luminous efficacy of warm-light LEDs matching that of cool-light in the 2025-2030 time range. It projects that warm and cool light LEDs will have comparable efficacy by 2028 (Pattison et al. 2018).

III. Courses of Action

Three courses of action may be taken to reduce the effects of artificial illumination on night sky observations:

1. Fund research for < 3000 K LEDs through federal grants.
2. Mandate the use of warm-light LED illumination on federally funded projects.
3. Offer tax incentives for communities to use conservative illumination.

i. Federal Grants

Federal grants could be used as an incentive for research groups and industry to further develop warm-light alternatives to current LEDs. If adequately funded, the development timeline for warm-light LEDs could accelerate to be completed before the predicted 2025 time-frame. Acquiring an equally economical but lower-polluting LED will slow the spread of cool LEDs. Stopping the explosive growth of cool lighting as quickly as possible will reduce long-term light pollution. If the acquisition of warm-light LEDs is too slow, more cool LEDs will continue to be installed, increasing the effort required to reduce light pollution.

A series of competitive federal grants could be instituted to stimulate research into low-color temperature LEDs. The Department of Energy could award multiple $100k-$250k grants based on the applicant's merit. These grants will primarily focus on industry research and development. The direct effects of accelerated research will decrease light pollution directly and quickly. However, there would be limited public investment outside of research and development groups.

ii. Federal Mandates

The federal government could mandate changes to artificial illumination on government projects. Federal land, interstate infrastructure, and federally funded projects can all be influenced directly by funding. A federal mandate may be proposed to change cool-light LED and high luminescence lighting to warm-light and lower luminescence LED lighting. The lighting change would happen at the end of the current light fixture's life cycle, where the maintainer will then replace the lighting source to one with warm white LED fixtures. If implemented by 2025, most cool-light LEDs at the end of their eight-to-ten-year lifespan will be replaced by warm LEDs of equivalent efficacy and lifespan (Eaves 2021; Pattison et al. 2018). The cost to the federal government would be negligible. However, there will be limited public investment in the project, and this may not increase dark-sky awareness.

iii. Federal Incentives

To promote public investment, the federal government could offer incentives to communities conforming with IDA dark-sky places standards. Communities are one of five designations the IDA certifies that could be linked to federal incentives. A few of the requirements to become an IDA community include comprehensive lighting policy such as outdoor lighting shielding and a minimum of two dark sky awareness events per year (*IDA Standards*). Incentive packages could be prioritized for the IDA conforming communities in proximity to national parks. These packages will provide extrinsic motivation for communities to change their lighting habits, decreasing the light pollution in nearby national parks. Incentive packages can also be targeted at specific communities near optimal dark-sky areas to limit the costs of implementation. Warm-light LED incentives would be similar to the tax break packages the Department of the Interior provides for preserving historic properties (Rehabilitation Credit, 2017). Table A compares all three courses of action by cost, investment, timescale and scope of implementation, and measurability of outcome.

	Federal Cost	**Public Investment**	**Timescale of Implementation**	**Scope of Implementation**	**Measurability of Outcome**
Course of Action I Federal Grants	Mid	Low	1-5 years	Research and Development	Mid
Course of Action II Federal mandate	Low	Low	8-10 years	Federal Land	High
Course of Action III Incentives	High	High	2-4 years	Near Dark-sky Areas	Mid

Table A: Courses of Action Comparisons. A summarized comparison of the three courses of action presented. Federal grants pose some cost to the federal government, with a short timescale to implement funding. Grants will directly affect R&D and success can be directly measured by progress made through research funded by the grants. Federal mandates of warm-light LEDs at the end of the current fixture's lifecycle have minimal cost to the federal government.

IV. Policy Recommendation

All three courses of action could be implemented in two phases. Phase one focuses on research and development of warm pc-LED lighting. Phase two focuses on national implementation of warm lighting through federal mandates and incentives.

i. Developing Economically Competitive Warm LEDs

The most cost-effective dark-sky policy implementation is installing the improved warm-light LED fixtures as they become economically viable. This constitutes an adequate investment in research and development (R&D) to facilitate a quick transition to warm-light LEDs. A series of federal grants could be competitively awarded by the Department of Energy. The DoE would award grants to industry research groups based on merit. An appropriate goal from R&D is a 2500 K or lower LED fixture with a usable life of 50,000 hours and luminous efficacy of 110 lumens per watt. These parameters mirror current highly efficient cool-light LED fixtures. This phase could last about five years. As time progresses without a warm-light LED implementation, more cool-light LED fixtures will be installed and need replacement. I recommend that the Department of Energy awards $100k-$250k grants across a five-year timespan for a total of one-to-two million dollars allocated.

ii. Incentivizing and Distributing Warm LED Fixtures

Once adequate low-color-temperature LEDs are viable, the federal government can begin installing the warm LEDs on government projects at the end of the current light fixtures' lifecycle. Models created for life cycle cost analysis in retrofitting sodium doublet lighting with cool-light LEDs could be used with warm-light LEDs to estimate costs associated with a new lighting system (Beleny et al. 2021). Life-cycle cost analysis (LCCA) could account for operating parameters of warm-light LEDs - once research has improved their efficiency to rival cool-light LEDs - to predict the economic performance of a lighting system (ibid). Small scale implementation of warm-light LEDs could ensure additional costs of installing new LEDs vs cool-light LEDs are negligible. It would take eight-to-ten-years to replace outdoor cool-light LED fixtures during routine replacement completely.

Once the overall efficacy of warm-light LEDs are economically viable according to LCCA, replacing cool-light LED with warm-light LED lighting could be a cheap and widespread implementation of dark-sky policy. Replacing federal lighting would decrease light pollution from federal projects without sacrificing efficiency. However, replacing federally owned lights will not decrease light pollution significantly by itself. Lighting by private consumers will still pose a significant source of pollution. Introducing federal lighting mandates could decrease United States light pollution, but this is not a solution by itself.

To remedy this, the federal government could offer incentives to residential customers and private businesses to conform to the IDA standards through tax incentives and credits. Communities that comply with the IDA standards would receive a 33% federal tax deduction from money spent on warm LED fixtures. This federal tax deduction program would raise awareness of dark-sky preservation policy and make citizens more aware of their contributions to light pollution.

Staggering government investment in dark-sky preservation between research and installation would reduce inefficiencies in policy implementation. Comprehensive research in efficient warm-light LEDs will allow a smooth transition to warm-light LED use. Minimal difference in cost, lifespan, and efficacy between warm and cool LEDs will decrease resistance to dark-sky policy.

V. Summary

The revolution in LED lighting has increased the scope of light pollution in the United States. We can combat this pollution as a nation by transitioning to equally efficient warm-light LEDs from the currently in-place cool-light LED fixtures. To measurably increase the quality of our visible night sky, individual and federal ownership of the luminous footprint will need to be addressed. The IDA produced evaluations that already act as the standard for measuring light pollution can be utilized by the federal government to measure the U.S.'s progress toward eliminating light pollution.

The unique disposition of the federal government can increase the speed of new, more environmentally friendly warm-light LEDs through research and development. The federal government could produce immediate results through incentive programs, and directly impact the United States' footprint by implementing warm-light LED fixtures in federal projects. The federal government can change cool-light LEDs to warm-light LEDs at the end of their eight-to-ten-year lifespan without incurring more cost than typical maintenance. Concurrently, the government can provide tax incentives to communities that adhere to dark-sky preservation standards. Combining all three courses of action will be needed to comprehensively reduce light pollution.

References

Belany, P., Hrabovsky, P., & Kolkova, Z. (2021). Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings. *Energy Reports*, 7, 2470-2483. https://www.sciencedirect.com/science/article/pii/S2352484721002602

Cinzano, P., & Falchi, F. (2014). Quantifying light pollution. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 139. https://doi.org/10.1016/j.jqsrt.2013.11.020.

Eaves, M. (2021). Playing the Long Game. *Nightscape*, 105 (1) 4-5. https://www.darksky.org/wp-content/uploads/2021/09/Nightscape-105-Summer-2021.pdf.

Hartley, R. (2020, December 18). *International Dark-Sky Association Biden Transition Letter*. https://www.darksky.org/our-work/lighting/public-policy/.

Holker, F., Moss, T., Griefahn, B., & Kloas Wener. (2010). The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. *Ecology and Society*, *15*(4). https://www.researchgate.net/publication/232688395_The_Dark_Side_of_Light_A_Transdisciplinary_Research_Agenda_for_Light_Pollution_Policy.

International Dark-Sky Association. (2022). https://www.darksky.org.

International Dark-Sky Place Standards. (2022). International Dark-Sky Association. https://www.darksky.org/our-work/conservation/idsp/become-a-dark-sky-place/.

Lamphar, H., Wallner, S., & Kocifaj, M. (2022). Modelled impacts of a potential light emitting diode lighting system conversion and the influence of an extremely polluted atmosphere in Mexico City. *Environment and Planning B: Urban Analytics and City Science*, *49*(2), 501–518. https://journals.sagepub.com/doi/epub/10.1177/23998083211012702.

New Mexico Statutes - Night Sky Protection, Pub. L. No. 74–12, Justia US Law (2006).

New York - Lighting Restrictions, Pub. L. No. 143, Public Buildings (PBB) (2015). https://www.nysenate.gov/legislation/laws/PBB/143.

Pattison, P., Hansen, M., & Tsao, J. (2018). LED lighting efficacy: Status and Directions. *Comptes Rendus Physique*, *19*(3), 134–145. https://www.sciencedirect.com/science/article/pii/S1631070517300932.

Pena-Garcia, A., & Sedziwy, A. (2020). Optimizing Lighting of Rural Roads and Protected Areas with White Light: A Compromise among Light Pollution, Energy Savings, and Visibility. *The Journal of the Illuminating Engineering Society*, *16*(2), 147–156. https://www.tandfonline.com/doi/full/10.1080/15502724.2019.1574138.

Rajkhowa, Rasna. (2014). Light Pollution and Impact of Light Pollution. *International Journal of Science and Research*, 3(10), 861-867. https://www.ijsr.net/get_abstract.php?paper_id=OCT14210.

Rehabilitation Credit, Pub. L. No. 26 U.S. Code 47 (2017). https://www.law.cornell.edu/uscode/text/26/47.

Schulte-Romer, N., Meier, J., Soding, M., & Dannemann, E. (2019). The LED Paradox: How Light Pollution Challenges Experts to Reconsider Sustainable Lighting. *Sustainability*, *11*(21). https://www.mdpi.com/2071-1050/11/21/6160.

Zissis, G., Bertoldi, P., & Serrenho, T. (2021). Update on the Status of LED-Lighting world market since 2018. *JRC Technical Report*. https://publications.jrc.ec.europa.eu/repository/handle/JRC122760.

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