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OPINION

Redefining efficiency for outdoor lighting

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Improvements in the luminous efficiency of outdoor lamps might not result in energy savings or reductions in greenhouse gas emissions. The reason for this are rebound effects: when light becomes cheaper, many users will increase illumination, and some previously unlit areas may become lit. We present three policy recommendations that work together to guarantee major energy reductions in street lighting systems. First, taking advantage of new technologies to use light only when and where it is needed. Second, defining maximum permitted illuminances for roadway lighting. Third, defining street lighting system efficiency in terms of kilowatt-hours per kilometer-year. Adoption of these policies would not only save energy, but would greatly reduce the amount of light pollution produced by cities. The goal of lighting policy should be to provide the light needed for any given task while minimizing both the energy use and negative environmental side effects of the light.

The United Nations has declared 2015 to be the International Year of Light and Light-based Technologies (UN IYL), for which issues of sustainability and development are of central importance. Because artificial lighting accounts for an estimated 19% of all electrical energy use worldwide[1], changes in lighting can have a large influence on energy consumption, carbon footprint, and environmental effects. The most visible policy response to excessive energy use for lighting has been restricting sales of new lamps to "energy efficient" models with higher luminous efficiency. During the IYL, for example, the European Eco-Design Directive (2009/125/EC) will ban sales of Mercury vapor lamps, 18 million of which were still installed for road lighting in Europe in 2007[2]. Unfortunately, policy-driven improvements in efficiency alone are unlikely to reduce energy use and CO2 emission, because they leave users free to use more light.

In this forum, we discuss outdoor lighting, an important component (~15-20%) of total illumination that has been increasing globally at a rate of 3-6% per year[3,4]. A period of rapid change in installed road lighting is currently underway, so the UN IYL offers a unique chance to make lighting practices more sustainable. We present three policy recommendations for outdoor night lighting that would not only reduce energy use, but would also mitigate an unintended consequence of artificial light use outdoors: light pollution.

Background

Over the last decades, there has been a shift in the reference points for night and darkness, as younger generations are often not aware of past conditions. These reference points serve as baselines for human perception to assess environmental changes.

The drift of baselines away from true natural conditions, and the resulting change in perception of differences, is called a shifting baseline syndrome[5]. In the context of artificial light at night, there are several shifting baselines. The first is our understanding of what a "normal" night looks like. The second is subjective perception of the relationship between lighting environment and safety and security. The third is decreased experience using non-visual senses at night (e.g. hearing and balance). These shifting baselines explain how incremental changes over decades have radically altered the night environment in highly developed regions without most people noticing: the cloudy night sky over cities is today thousands of times brighter than it was while nocturnal animals evolved[6], and approximately 20% of the global population cannot see the Milky Way where they live[7].

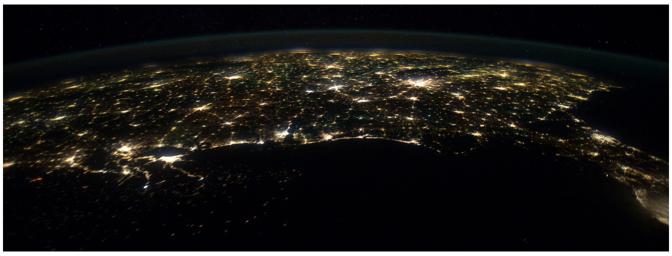

Fig. 1: In only a few human generations, the nighttime environment radically changed over large fractions of the Earth's surface. Photograph of the United States at night from the International Space Station is courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center (ISS030-E-55521).

From a policy standpoint, the purpose of outdoor lighting is the same as indoor lighting at night: to allow activity to continue after the sun has set. However, whereas most people turn lamps off when they sleep, much of the installed outdoor lighting continues to burn until the arrival of dawn. The forthcoming UN IYL celebrates the remarkable advances in our ability to manipulate light, and opens an ideal window-of-opportunity for policymakers to reconsider nighttime lighting strategies.

City lights installed in the 20th century suffer from three problems: First, dusk-till-dawn continuous lighting is appropriate for urban cores, but does not reflect street use patterns or the desire for darkness at night in areas where nearly everyone is sleeping. Second, a considerable amount of light is emitted at angles only slightly below the horizontal. This practice allows increased pole spacing (reducing the cost of installing the system), but it also means that the scene contains highly glaring elements that cause the eye's pupil to contract, reducing visibility. This glare is exacerbated for the increasingly large fraction of older drivers who have reduced eye transparency. Third, some fraction of light is emitted upward, and this waste light bears primary responsibility for the problem of skyglow[8].

Light emitting diodes (LEDs) allow light to be directed with unprecedented precision and control over color. In contrast to traditional street lamps, LEDs can be instantaneously dimmed to 10% or turned off when light is not desired. While it may make short-term financial sense, a simple replacement of traditional luminaires with LEDs will unfortunately not address all of the problems of traditional street lamps. For example, problems of glare are often more pronounced on LED-lit streets both because of the extremely high luminance from the point-like sources of most LED lamps and their spectral character. The challenge faced by 21st century policymakers is to provide outdoor light where and when it is needed while reducing costs, improving visibility, and minimizing any adverse effects on plants, animals, and humans caused through exposure to unnatural levels of light at night[9-11].

The first legislation to limit outdoor light began several decades ago, in communities near astronomical observing sites. It is only recently that regional (e.g. Italian provinces like Lombardy) and national (Slovenia 2007, France 2013) laws regarding lighting have come into effect (see Table S1). Such laws tend to focus on limiting the amount of light that can be emitted directed upward into the sky, mandating dimming or turning lights off at certain times, or in some cases placing caps on the total number of lumens allowed. A selection of norms and laws is included in the supplemental Table S1.

Challenges

Outdoor lighting policy has generally been concerned with recommending minimum levels for road surfaces (e.g. European Standard EN13201, Table S1). Due to the high cost of electricity, much lighting infrastructure in Europe is actually below norm, so improvements in luminous efficiency make it easier to meet, or greatly exceed, these norms. Fig. 2 shows an example of a site over illuminated with "energy efficient" lamps.

Fig. 2: Aerial photograph of newly installed lighting in Rathenow, Germany (52°36.3′N 12°20.5′E). Under the new lamps, the illuminance of pedestrian crossings is 150 lux. This is far brighter than is needed, and the photo demonstrates that it is also out of character with the lighting in the rest of the city, where the illuminance has a maximum of ~20 lux. Photo by C Kyba.

Such unexpected responses of humans to management interventions are a key source of uncertainty in the management of social-ecological systems[12]. Technological innovations intended to improve the efficiency of energetically costly systems do not necessarily reduce energy consumption or environmental impact. Cases where higher efficiency leads to greater consumption rather than reduced energy use are known as rebound effects[13]. For example, although luminous efficiency has doubled over the past 50 years in the UK, per capita electricity consumption for lighting increased fourfold[14]. Worldwide, the total cost of light consumption (including the cost of both lamps and energy) remains near 0.7% of gross domestic product (~440 billion US$ in 2005), regardless of lighting technology[15]. Policymakers should therefore expect that without usage limits, reduced lighting cost will increase illumination[13].

Recommendations

Our first policy recommendation is a transition to **need-based lighting**. Lighting should only be provided where and when it is needed. Streetlight emission above the horizontal serves no useful purpose, and should be prohibited to prevent skyglow[8]. Near-horizontal downward directed light should be minimized to the greatest extent possible to prevent glare. In many cases, more careful distribution of light would allow a reduction in illuminance, increasing visibility while saving money and energy. In suburban and rural locations with very little activity after midnight, LED lamps could be dimmed to 10% of their flux until morning traffic begins. Ideally, motion sensors could be used to run lamps at high power only during periods with activity. Many tens of millions of streetlamps will be installed in the current period of rapid change, and they are unlikely to be replaced for several decades. Lighting departments should therefore be instructed to ensure that any luminaire replacements be compatible with the requirements of future adaptive lighting systems.

Our second recommendation is defining **maximum illuminations**. Studies are necessary to determine context specific minimum light levels for activities such as walking, or operating cars and heavy equipment. Standardization bodies should synthesize this research, and provide not only minimum light levels, but also define conservative associated maximum values appropriate for an area. Manufacturers and lighting departments will have a stronger incentive to avoid over-lighting if laws regulating maximum values are in place. In the interests of transparency and good governance, municipalities should annually report their light use in terms of lm km^{-1} (lumens per km of roadway) for each hour of the night.

Defined maximum illumination levels will help prevent a ratchet-like increase in illumination levels over time due to the shifting baseline syndrome (areas with newly increased illumination make adjacent areas appear dark). It is also worth considering the provocative idea that with modern automobile headlights, lighting is no longer necessary for traffic safety on every urban road. Major energy savings would be possible if street lighting were replaced with modest illumination of pedestrian areas, paired with innovative techniques for highlighting roadway hazards. For example, enhanced contrast of illuminated crosswalks against unlit streets could even improve observation of pedestrians in conflict zones. Policymakers and funding agencies should therefore encourage the development and testing of novel lighting concepts.

Our final recommendation is to adopt a **new definition of efficiency** in urban street lighting. The goal of lighting policy should be the efficient provision of light: providing only the amount of light required for a given task, while minimizing negative environmental effect and energy use. This concept is different from the narrow focus on improving luminous efficiency that has dominated development and policy in recent years[1,13]. In the context of street lighting systems, a more appropriate measure for reporting energy efficiency is $kWh(kmy)^{-1}$ of roadway (kilowatt hours per kilometer-year). For any given street, this measure allows apple-to-apple comparisons of radically different lighting delivery systems. For example, adaptive lighting systems that dim or turn off lamps when not needed may use far less energy in a year than traditional systems, regardless of the luminous efficiency of the lamps involved.

Conclusions

The total energy required for street lighting has continued to grow despite the fact that the luminous efficiency of streetlamps has been increasing for centuries. The annual cost of providing street lighting worldwide is currently tens of billions of dollars per year, and the costs of converting older street lamps to high luminous efficiency LEDs will be considerable. Unfortunately, complete conversion to LEDs is actually unlikely to reduce energy consumption, unless it occurs together with policy designed to prevent rebound effects. By adopting the three policy recommendations outlined here, real reductions in energy use are possible, without compromising the public experience and use of outdoor lighting.

Notes and references

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Electronic Supplementary Information (ESI) available: **Table S1**: A selection of norms, decrees and laws demonstrates that there is a diverse range of policy, a diverse range of actors and expertise, different sizes, and different ways of accomplishing the goals. Legislation to limit outdoor light began several decades ago in communities near astronomical observing sites, but it is only recently that regional (e.g. Italian provinces like Lombardy) and national laws (Slovenia 2007, France 2013) have come into effect.

1. International Energy Agency, *Lights labour's lost: policies for energy-efficient lighting*, OECD/IEA, Paris, 2006.
2. P. Van Tichelen *et al.*, *Preparatory studies for eco-design requirements of EuPs Final Report Lot 9: Public Street lighting*, Study for the European Commission DGTREN Unit D3, Vito, 2007.
3. F. Hölker et *al.*, The dark side of light: a transdisciplinary research agenda for light pollution policy. *Ecol. Soc.*, 2010, **15**(4), art. 13.
4. K. Narisada and D. Schreuder, *Light pollution handbook.* Springer, Dordrecht, The Netherlands, 2004.
5. D. Pauly, Anecdotes and the shifting baseline syndrome of fisheries. *Trends Ecol. Evol.,* 1995, **10,** 430.
6. C. C. M. Kyba, T. Ruhtz, J. Fischer and F. Hölker, Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. *PLoS ONE,* 2011, **6**(3), e17307.
7. P. Cinzano, F. Falchi and C. D. Elvidge, The first world atlas of the artificial night sky brightness. *Mon. Not. R. Astron. Soc.,* 2001, **328**, 689-707.
8. F. Falchi, P. Cinzano, C. D. Elvidge, D. M. Keith and A. Haim, Limiting the impact of light pollution on human health, environment and stellar visibility. *J. Environm. Managem.,* 2011, **92**, 2714-2722.

9. C. Rich and T. Longcore, Eds., *Ecological Consequences of Artificial Night Lighting* Island Press, 2006.

10. K. J. Navara and R. J. Nelson, The dark side of light at night: physiological, epidemiological, and ecological consequences. *J. Pineal Res.,* 2007, **43**, 215-224.

11. R. G. Stevens, C. G. Brainard, D. E. Blask, S. W. Lockley and M. E. Motta, Adverse Health Effects of Nighttime Lighting: Comments on American Medical Association Policy Statement. *Am J Prev Med,*. 2013, **45**, 343-346.

12. M. Schlüter *et al*., New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Nat. Res. Model.,* 2012, **25**, 219-272.

13. J. Jenkins, T. Nordhaus and M. Shellenberger, *Energy emergence: rebound and backfire as emergent phenomena*. Breakthrough Institute, Oakland, 2011.

14. R. Fouquet and P. J. G. Pearson, Seven centuries of energy services: The price and use of light in the United Kingdom (1300-2000). *Energy J.,* 2006, **27**, 139-177.

15. J. Y. Tsao, H. D. Saunders, J. R. Creighton, M. E. Coltrin and J. A. Simmons, Solid-state lighting: an energy-economics perspective. *J. Phys. D. Appl. Phys.,* 2010, **43**, 354001.

Supplementary Materials:

Table S1: A selection of norms, decrees and laws demonstrates that there is a diverse range of policy, a diverse range of actors and expertise, different sizes, and different ways of accomplishing the goals. Legislation to limit outdoor light began several decades ago in communities near astronomical observing sites, but it is only recently that regional (e.g. Italian provinces like Lombardy) and national laws (Slovenia 2007, France 2013) have come into effect.

Country, Region, City	***Name, type***	***Year***		***Measures***	***Regulated type of light***	***Impetus***
USA, Arizona, Flagstaff [1]	ordinance	1958	city	search light embargo	searchlights	dark sky protection close to astronomical observatories
USA, Arizona, Flagstaff [2]	code	1989/2011	city	lumen/acre	street lighting	dark sky protection close to astronomical observatories
Switzerland, Lucerne [3]	illumination concept	2008	city	lighting level, switch-off at 23:00, CCT = 3000 K no color lighting	facade illumination, shop lighting, street lighting	lighting design, environmental protection, energy consumption reduction
Germany, Berlin [4]	decree	2010	city	reduced lighting intensity, warm white light, switch-off 00:00 of facade illumination	street lighting facade illumination	lighting design, environmental protection, reduction CO_2 emissions, energy consumption reduction, road safety
Canada, Alberta, Calgary [5]	bylaw	2002/2008	city	lower wattage, downward lighting	street lighting	energy consumption reduction, glare reduction, light pollution reduction
Italy, Lombardia [6]	law	2000	province	full cut-off fixtures, luminances < 1 cd/m², 30% reduction at 00:00	street lighting,	dark sky protection close to astronomical observatories , energy consumption reduction
Spain, Canary Island La Palma [7]	decree	1988	province	full cut-off fixtures blue light <15%	outdoor lighting	dark sky protection close to astronomical observatories
Spain, Andalusia [8]	decree	2007	province	zonification, ULR<1% in E1	street lighting	environmental and landscape protection, dark sky protection close to astronomical observatories
Italy, Alto Adigio [9]	law	2011	province	inventory, full cut-off fixtures reduction 00:00-06:00, luminances < 2 cd/m² CCT < 4000 K	street lighting, facade illumination, sports lighting	environmental and landscape protection, energy consumption reduction
Slovenia [10]	decree	2007	national	full cut-off fixtures, < 50 kWh/inhabitant	street lighting facade illumination	dark sky protection, energy consumption reduction
France [11]	decree	2012	national	switch-off at 01:00-06:00	advertising lighting	energy consumption reduction, reduction CO_2 emissions
France [12]	decree	2013	national	switch-off at 01:00 1 h after office usage	facade illumination office illumination	energy consumption reduction, reduction CO2 emissions
Germany, light immission regulation [13]	recommendation	1993	regional	< 1 lux on dormitory window	room brightening (through non-public lighting)	light immission reduction

European Union [14]	norm	2003 2013 (proposal)	trans-national	minimum illuminance and luminance values, homogeneity criteria, maximum values proposed	street lighting	road safety, standardization
European Union [15]	Ecodesign directive	2009	trans-national	energy efficiency	street lighting, domestic lighting	energy consumption reduction, reduction CO2 emissions
Council of Europe member states [16]	resolution	2010	trans-national	quantification and reduce light pollution	outdoor lighting	environmental protection, dark sky protection, energy consumption reduction

[1] http://www.flagstaffdarkskies.org/international-dark-sky-city/flagstaffs-battle-for-dark-skies/

[2] Flagstaff Lighting Code, 2011, http://www.nofs.navy.mil/about_NOFS/staff/cbl/Flagstaff.LC.2011.pdf

[3] Plan Lumière-Das Beleuchtungskonzept für die Stadt Luzern, Mai 2008, http://www.stadtluzern.ch/de/aktuelles/projekte/projekteaktuell/?action=showthema&themenbereich_id=16&thema_id=115

[4] Stadtbild Berlin, Lichtkonzept, Feb. 2011. http://www.stadtentwicklung.berlin.de/bauen/beleuchtung/de/lichtkonzept.shtml

[5] EnviroSmart streetlight retrofit, 2002-2005, http://www.calgary.ca/Transportation/Roads/Pages/Traffic/Traffic-signals-and-streetlights/Envirosmart-streetlight-retrofit/EnviroSmart-streetlight-retrofit.aspx
Land use bylaw, 2008, http://www.calgary.ca/PDA/DBA/Documents/Calgary-Land-Use-bylaw-1P2007/bylaw_1p2007.pdf

[6] Regione Lombardia, Legge Regionale N. 17: Misure urgenti in tema di risparmio energetico ad uso di illuminazione esterna e di lotta all'inquinamento luminoso, 27 marzo 2007, http://consiglionline.lombardia.it/normelombardia/accessibile/main.aspx?view=showpart&selnode=lr002000032700017&idparte=lr002000032700017

[7] Ley sobre Protección de la Calidad Astronómica de los Observatorios del IAC (Ley 31/1988 del 31 de octubre) BOE Num 264 de 3 de noviembre de 1988 http://www.iac.es/servicios.php?op1=28

[8] Protección del Cielo Nocturno, Decreto 357/2010, de 3 de agosto 2010, http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.30d4b35a97db5c61716f2b105510e1ca/?vgnextoid=078259cdd5405110VgnVCM1000000624e50aRCRD&vgnextchannel=3fbdc414cc389210VgnVCM10000055011eacRCRD&lr=lang_es (law)
http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.30d4b35a97db5c61716f2b105510e1ca/?vgnextoid=f58581675e8aa210VgnVCM1000001325e50aRCRD&vgnextchannel=3fbdc414cc389210VgnVCM10000055011eacRCRD&lr=lang_es (decrete)

[9] Approvazione dei criteri per le misure di contenimento dell'inquinamento luminoso e per il risparmio energetico, Bollettino Ufficiale n. 31/I-II del 31/07/2012 http://www.provincia.bz.it/agenzia-ambiente/energia/inquinamento-luminoso.asp

[10] 4162. Uredba o mejnih vrednostih svetlobnega onesnaževanja okolja Na podlagi tretjega in petega odstavka 17. člena Zakona o varstvu okolja (Uradni list RS, št. 39/06 – uradno prečiščeno besedilo, 49/06 – ZMetD, 66/06 – odl. US in 33/07 – ZPNačrt) izdaja Vlada Republike Slovenije U R E D B O o mejnih vrednostih svetlobnega onesnaževanja okolja, German translation: http://www.wua-wien.at/home/administrator/components/com_astatspro/getfile.php?id=105

[11] Décret n° 2012-118 du 30 janvier 2012 relatif à la publicité extérieure, aux enseignes et aux préenseignes, http://www.legifrance.gouv.fr/affichTexte.do;jsessionid=3FF25512A55E385C6AACF9AD92AA2A66.tpdjo05v_2?cidTexte=JORFTEXT000025240851&categorieLien=id

[12] Arrêté du 25 janvier 2013 relatif à l'éclairage nocturne des bâtiments non résidentiels afin de limiter les nuisances lumineuses et les consommations d'énergie, http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000027003910&fastPos=1&fastReqId=1850617855&categorieLien=id&oldAction=rechTexte
[13] Bund/Länder - Arbeitsgemeinschaft für Immissionsschutz: Hinweise zur Messung, Beurteilung und Minderung von Lichtimmissionen, 2012, http://www.lung.mv-regierung.de/dateien/laerm_licht_neu.pdf
[14] CEN EN 13201-2: Road lighting - Part 2: Performance requirements (2003), http://esearch.cen.eu/esearch/Details.aspx?id=11052965
[15] Commission Regulation (EC) No 244/2009 of 18 March 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009R0244:EN:NOT
[16] Noise and light pollution, Parliamentary Assembly Council of Europe Resolution 1776 (2010), http://assembly.coe.int/Main.asp?link=/Documents/AdoptedText/ta10/ERES1776.htm