Dark sky park and environmental friendly luminaires with adjustable light distribution, color and luminous flux: light pollution reduction in Hungarian settlements

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Abstract

The International Dark Sky Association (IDA) has a set of requirements for public lighting used in dark sky parks. In Hungary, many settlements still use compact fluorescent and sodium lamps that do not fulfill these requirements. To improve the circumstances of public illumination of dark sky parks in Hungary, we have performed lighting reconstructions at two villages, as a pilot project for light pollution reduction and scientific purposes. As a first step, the public lighting system was reconstructed, so that it satisfied the requirements of the IDA. We designed new LED luminaires with optimal spectral power distribution and optical properties to provide the necessary luminous intensity and reduce light pollution at the same time. The new system has a two-step illumination profile: (i) Early night, after sunset, when the traffic is still high, warm white LEDs are applied to ensure sufficient lighting coming to the roads and pavements with a wide beam of light and 13.1 lx average horizontal illuminance. (ii) Late night, when the traffic is low, the illumination switches to amber LEDs that have a narrower light beam to minimize light pollution and provide sufficient visibility with 3.9 lx average horizontal illuminance. This approach can be an optimal illumination construction to reduce the light pollution of public lighting at night.

Keywords: light pollution, dark sky park, lighting reconstruction, amber LED, LED luminaires

1 Introduction

Light pollution means the increased level of skylight caused by outdoor lighting systems used for public or ornamental lighting in inhabited areas [1]. Light pollution is damaging to astronomical observation and has significant environmental, ecological and human health issues. It hinders astronomical observation by affecting the visibility of diffuse sky objects like nebulae and galaxies. Many of them are invisible in heavily light-polluted skies above major urban areas. The direct form of light pollution arises when light emitted by artificial light sources directly disturbs observation, for example by getting additional light to a camera sensor compared to the circumstances under natural sky. Indirect reflection from large illuminated surfaces can also cause similar effects and has a significant contribution to the phenomenon called skyglow. Skyglow originates when light propagating into the atmosphere directly from upward-directed or incompletely shielded sources, or after reflection from the ground or other surfaces. Skyglow is partially scattered back toward the ground, producing a diffuse glow that can be seen from large distances. Skyglow typically can be noticed over cities and towns [2,3].

Artificial night lighting also has a harmful impact on ecological systems [4] distinguished ecological light pollution, which alters natural light regimes in terrestrial and aquatic ecosystems, from astronomical light pollution. According to their definition, ecological light pollution includes chronic or periodically increased illumination, unexpected changes in illumination, and direct glare. The influence of artificial light to the ecological system is manifold: ‘Animals can experience increased orientation or disorientation from additional illumination and are attracted to or repulsed by glare, which affects foraging, reproduction, communication, and other critical behaviors. Artificial light disrupts interspecific interactions evolved in natural patterns of light and dark, with

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serious implications for community ecology'[4]. A special form of ecological light pollution is when an artificial surface reflects polarized light that due to its polarization characteristics changes the behaviour of polarotactic animals. This phenomenon was first introduced by [5] and characterized as follows: 'Polarized light pollution includes light that has undergone linear polarization by reflecting off smooth, dark buildings, or other human-made objects, or by scattering in the atmosphere or hydrosphere at unnatural times or locations. Artificial polarizers can serve as ecological traps that threaten populations of polarization-sensitive species. Artificial polarized light can disrupt the predatory relationships between species maintained by naturally occurring patterns of polarized light, and has the potential to alter community structure, diversity, and dynamics.

The best places to study the natural night sky and natural ecological environment are dark sky parks. According to the definition of International Dark-Sky Association (IDA), an IDA International Dark Sky Park is a land possessing an exceptional or distinguished quality of starry nights and a nocturnal environment that is specifically protected for its scientific, natural, educational, cultural heritage, and/or public enjoyment [6].

It has been ten years since the first dark sky park was established in Hungary. Today, there are three such specially protected areas in the country: in Zselic, Hortobágy and Bükk. These areas belong to national parks, in the vicinity of which typically small settlements are located. In these villages, the public lighting is realized mainly with luminaires using compact fluorescent lamps (CFL) of 36 W power. According to the rules of the IDA [7] such illumination is prohibited in dark sky parks, due to the relatively large ratio of luminous flux emitted towards the upper hemisphere. This urged the need to modernize and reconstruct public lighting, where the protection of the night sky and the environment were also primary goals. The best alternative to the luminaires using CFL technology was to change the luminaires to LED-based street lighting with customized emission spectrum. Our motivation was twofold: i) change lighting according to IDA rules and ii) observe environmental impacts of new LED technology in a Living Environmental Laboratory for Lighting (LELL).

LED based lighting solutions have become widespread all over the world in the last ten years.[8] proposed an energy efficient automated LED-based street lighting design for rural traffic illumination in as early as 2014. The common components of LEDs used for public lighting are white LEDs using the so called phosphor converting (PC) technology, driven by power supplies in switching mode and are covered by flat glass elements. In 2019, many manufacturers see new possibilities to reduce energy consumption by applying smart control of the lighting systems. In some cases, however, the contrary can be found. [9] observed a rebound effect with LEDs on global scale. Instead of energy reduction on country level, in many countries more light was installed to replace high pressure sodium (HPS) lamps under the banner of sustainability. The process was not cost efficient, because this change happened way before the lifetime of HPS lamps and the total luminous flux of the installed LEDs were higher than that of the former lamps causing increased light pollution worldwide. [10] pointed out that the usage of white LEDs has a bigger ecological impact compared to HPS lamps irrespective of the colour temperature. They used light traps with white LEDs and HPS lamps to capture phototactic insects. The former attracted 48% more insects and showed no significant change when the colour temperature was varied.

An early attempt of smart lighting control was proposed by[11], where dynamic street light control, that combines advanced information and communication technologies and citizens' involvement and engagement, is implemented in the smart city context. The parameters regarding light quality properties became an important value in the lighting industry. A large emphasis is placed on application-oriented utilization of lighting and also the implementation of cloud based management systems and IoT applications are spreading more and more [12]. Endeavours to reduce light pollution has only been realized in the form of pilot projects at some places in the world [13,14], by using amber LED lights.

Our goal was to construct an exemplary lighting system that provides sufficient light for public needs at night and also reduces light pollution compared to the former street lighting system. The pilot projects were elaborated in Bárdudvarnok and Répáshuta, where the former luminaires were replaced by our new LED-based models. The LELL system is used for measuring light pollution, environmental and ecological impacts at the same time. With adjustable intensity levels, we can directly study the effects of different intensity public lighting. In this paper, we present a light source design that was applied as a pilot solution to realize the above idea. This is the first product with adjustable spatial pattern, CCT and intensity of public lighting.

2 Materials and Methods

2.1 IDA criteria of lighting environment in dark sky parks

The basic criterium in dark sky parks is to follow the set of rules by the International Dark-Sky Association[7]. According to that, the luminaire housings need to be completely hooded so that the luminous flux entering to the upper hemisphere above the horizon, i.e. the upwards light output ratio (ULOR), is zero. It is not enough to fulfill this criterium in the laboratory, but the luminaires should be installed carefully to satisfy the criteria at the spot of the operation.

Previously, the accepted upper limit of the correlated colour temperature (CCT) used to be 4000 K. However, studies have shown, that by the spreading of cool white LEDs, the high-intensity blue peak of their spectral power distribution has a harmful effect on the living environment and ecosystem. The latest studies [15] have described a direct correlation between the colour of public lighting and tumour formation, e.g. in breast, prostate and colorectal cancers. Other studies have surveyed the impact of several lamps with different spectral distribution on human health (e.g. melatonin suppression), ecology (e.g. induced photosynthesis in plants, direct response to light of different organisms) and star visibility [16,17]. Based on the results of the recent year studies, the upper limit of CCT has been restricted to 3000 K for various reasons, including energy saving, protection of human health, conservation of nocturnal wildlife and protection of natural nightscapes. It is recommended, however, to apply even warmer illumination in a natural environment.

CCT is usually not the best metric to measure the ecological impact of illumination. In their study, [16] suggested new indices to characterize better the various impacts of different lights: Melatonin Suppression Index (MSI), Induced Photosynthesis Index (IPI) and Star Light Index (SLI). IDA determined another index: the ratio of the radiated energy content below 550 nm must not exceed 25 % of the total radiated energy of the light source. Besides, the ratio of scotopic-to-photopic luminous flux (S/P ratio) is also limited to 1.3.

2.2 Directives of light source development

Based on Rayleigh scattering, the extent of light pollution at night clear sky largely depends on the spectral power distribution of the given light source. Clouds, however, above an inhabited area with public lightings can increase the brightness of the night sky by reflecting back upward coming light [2]. In rural areas, where there is no artificial lighting, clouds can turn the night sky even darker [18]. The optimal choice of the light source can be the amber LED, that has a minimal or zero output of spectral power in the blue wavelength range. If a light source has high spectral output in the 400 nm - 470 nm wavelength range, the scotopic-to-photopic luminous flux ratio is higher than light sources with the same total output with less blue content. Since scotopic vision plays a primary role in the visibility of the night sky, it seems brighter by applying cool white public illumination even if the luminance on the asphalt road is equal to that from alternative light sources [16].

Amber LEDs are available with basically two technologies. (1) The first solution applied pure semiconductor technology (GaAsP. GaP. AlGaInP), resulting in a narrow range emission of ~ 15 nm – 20 nm full width at half maximum (FWHM) in the wavelength range of 570 nm – 610 nm and the typical luminous efficacy is in the range of 20 lm/W – 40 lm/W. (2) The second solution applies the amber LED with phosphorus converting (PC) technology. This technology works in the same way as PC white LEDs, where a light emitting phosphor layer is excited by the photons of a blue LED in the 430 nm – 470 nm spectral range. The difference is in the conversion rate of blue photons that can adjust CCT. 90 % - 95 % of the total output of the blue LED is used for exciting the phosphor layer, that results a wider spectrum of ~ 80 nm – 110 nm (FWHM) with a peak wavelength around 590 nm and typically 70 lm/W – 80 lm/W luminous efficacy.

The luminous efficacy of LED illumination used for public lighting today is 140 lm/W – 160 lm/W. Thus, applying amber LEDs itself means a setback compared to white LEDs. However, the optical efficiency of the hood and lens, the luminous efficacy and cooling of the LED also contribute to the total efficiency of the system. These aspects had to be considered during the construction of the lighting system.

Hood: General flat glass or polycarbonate hood without anti-reflective coating, the optical efficiency of which is less than 90 %, is not sufficient for public illumination. The optical loss of such luminaires would be 25 % - 30 %. As a solution, the optical system of the PearlLight luminaire family, designed by the Hungarian luminaire manufacturer Hungaro Lux Light Ltd., Veszprém, was used, the geometric construction of which enabled only slight decrease of luminous efficiency than in the case of flat glass solutions.

To fulfill the condition of ULOR = 0, further shading elements had to be added to the design. The basic concept of the novel optical solution was the following (Fig. 1): the compact hood swallows up around the LED lens as a layer of the sphere, and the light can exit the lamp body only through this layer. This ensures that the incident angle of the light going through the hood is always less than 40°. In this range, the transmittance was practically the same as at perpendicular incident angles. To further reduce losses from reflections, an anti-reflective coating was applied on both sides of the hood, developed in cooperation by Hungaro Lux Light Ltd, Budapest University of Technology and Economics and the Institute of Technical Physics and Materials Science of the Hungarian Academy of Sciences, Budapest.

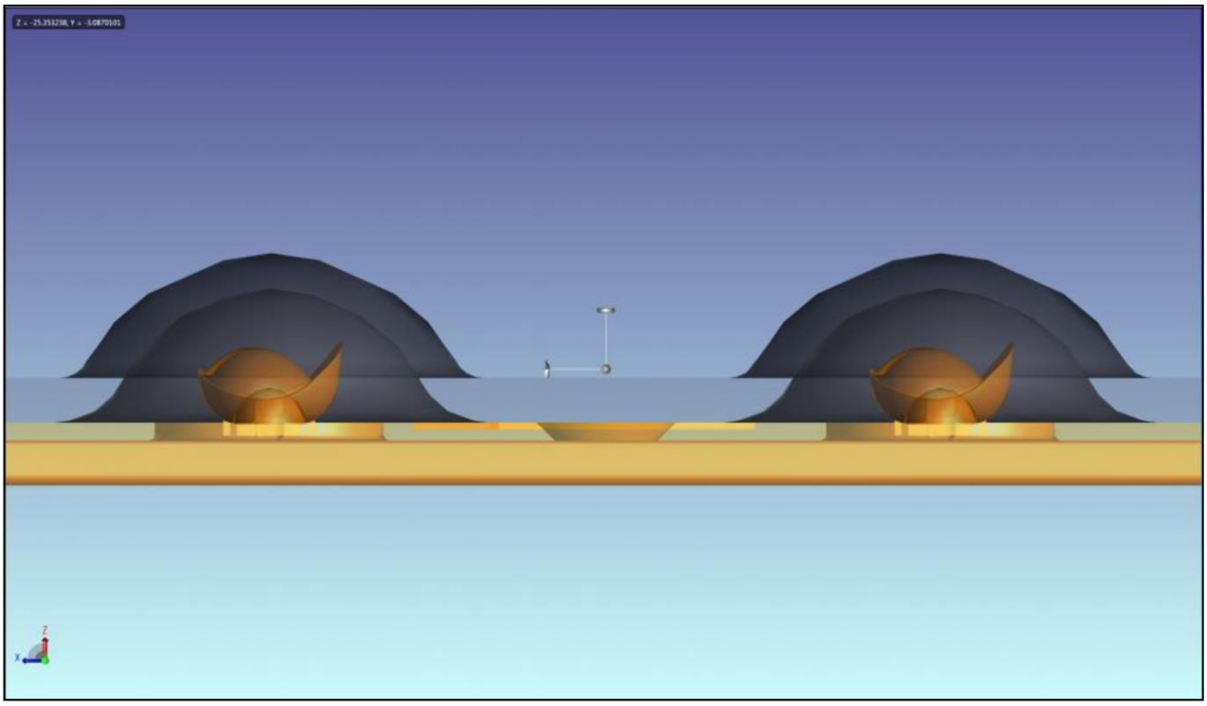

Figure 1: Model schematics of the hood and lens of the lamp bodies designed for lighting reconstruction.The model was created by the software PearlLight+, developed by Hungaro Lux Light Ltd, Veszprém, Hungary. The same concept was used for both warm white and PC amber LEDs. The compact hood swallows up around the LED lens as a layer of the sphere, and the light can exit the lamp body only through this layer.

Lens: The construction of the LED lens design was a free form design performed by the software PearlLight+, developed by Hungaro Lux Light Ltd. The software was able to suggest an optimal lens shape concerning the given conditions (column height, column distance, road width, road category, lighting-class etc.) at the location of application. The user also could adjust the weight of the different parameters, taken into account during the design of the lens shape by the software. The software also could simulate the optical properties of luminaires with anti-reflective coating where the user could define the initial shape of the bodies, total luminous flux and the parameters of the coating. After performing the calculations, we got the ideal lens shape as a result (Fig. 2), that could be saved in standard CAD output formats and used for preparing an injection moulding tool.

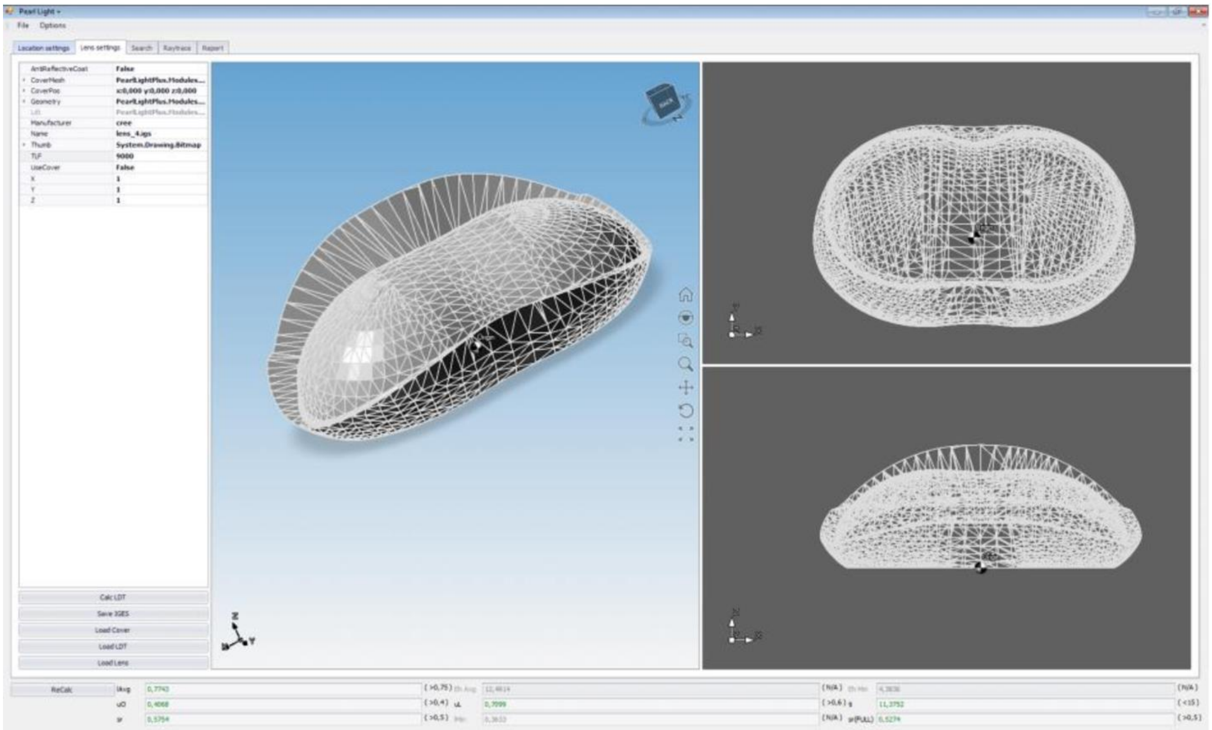

Figure 2: Optimal shape of the hood of the LED lamp body constructed with PearlLight+ optical designer software. The software was able to suggest an optimal lens shape concerning the given conditions (column height, column distance, road width, road category, lighting-class etc.). After performing the calculations, the ideal lens shape is obtained as a result.

Cooling: The printed circuit board (PCB) containing the LEDs are directly contacted with the housing of the luminaire and thus with the cooling surface. The results of this technology have been published earlier [19]. The advantage of this effective solution is that the low working temperature of LEDs can be ensured and kept stable even under high (>30 °C) outdoor temperatures. The compact model of cooling was designed by using computational fluid dynamics (CFD) simulations performed by Budapest University of Technology and Economics.

2.3 Public lighting reconstruction

A change in lighting technology was realized at two settlements in two national parks in Hungary, in December 2018. Bárdudvarnok (GPS: 46° 19′ 40.76″ N, 17° 41′ 15.68″ E) and Répáshuta (GPS: 48° 2′ 55.5″ N, 20° 31′ 41.41″ E) are both in the area of a dark sky park (Zselic Starry Sky Park and Bükk Starry Sky Park, respectively), being an ideal choice for studying the effect of lighting reconstruction to light pollution of public illumination compared to the previous state before the reconstruction. The measurements whether the optical properties of the light sources satisfy the conditions mentioned above was performed by an independent accredited photometry laboratory, LightingLab Calibration Laboratory Ltd., Veszprém, who specializes in photometric laboratory calibrations and on-site illuminance measurements.

3 Results

At the two settlements where the lighting reconstructions were performed, the goal was to provide the necessary public illumination and to reduce light pollution at night at the same time. It could only be performed with necessary compromises. A two-step illumination profile was elaborated: (i) Early night, after sunset, when the traffic was still high, warm white LEDs with PC technology and with a wide beam of light were applied to ensure sufficient illumination on the roads and on pavements (13.1 lx). (ii) Late night, when the traffic was low, the illumination switched to PC amber LEDs, that had a narrower light beam to minimize light pollution and still providing sufficient visibility on the road (3.9 lx). The luminous intensity distribution created by the two different optics of the lighting system is shown in Fig. 3. The luminous efficacy of the system was 100 lm/W in the warm white LED state, and 52 lm/W in the PC amber LED state.

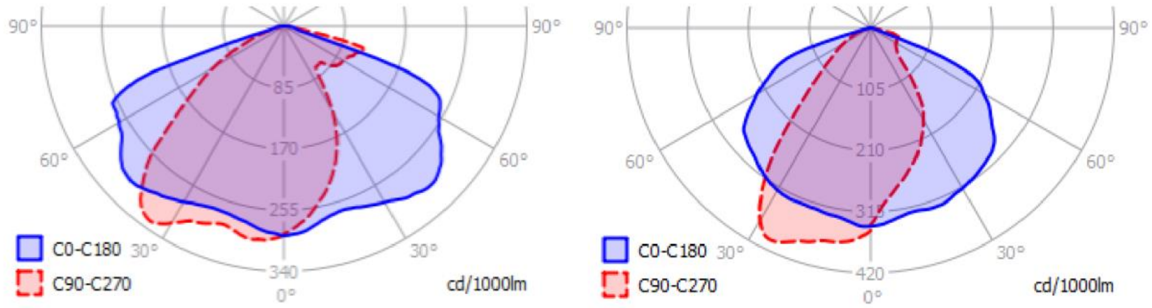

Figure 3: Light intensity distribution of an individually designed wide band (left) and narrow band (right) illumination profile.

Figure 4: Comparison of illumination before (top and upper middle image) and after (bottom and lower middle image) the public lighting reconstruction in Bárdudvarnok. The defocused photos in the middle demonstrate the intensity changes of the lamps.

An important parameter of LELL is the spectrum of illumination. Fig. 4 shows an example of a photo taken in Bárdudvarnok before and after the lighting reconstruction (the camera settings were the same while making the comparisons, respectively). The ULOR of the installed luminaires was 0. Fig. 5 shows a photograph of a street in Bárdudvarnok and the light intensity distribution displayed with false colours after the lighting reconstruction. The amount of luminous flux towards the horizon and the upper hemisphere was negligible. Fig. 6 gives a comparison of the spectra of the old lighting system with CFL light sources and the new, LED-based system. In the case of the old system, the ratio of spectral output below 550 nm was 46 %, that is almost twice as much as accepted by IDA regulation. In the new system, this amount is only 19 % in the active period of the early night (warm white LED state) and 5 % in the resting period of late night (PC amber LED state). The CCT value of the old illumination system was 3600 K, while with the new system, it was 2400 K in the early night period and 1900 K in the late night period. The scotopic-to-photopic ratio of the light current was above 1.3 in the old system, whereas it improved to 0.9 and 0.44 in the new system in the early and late night period, respectively.

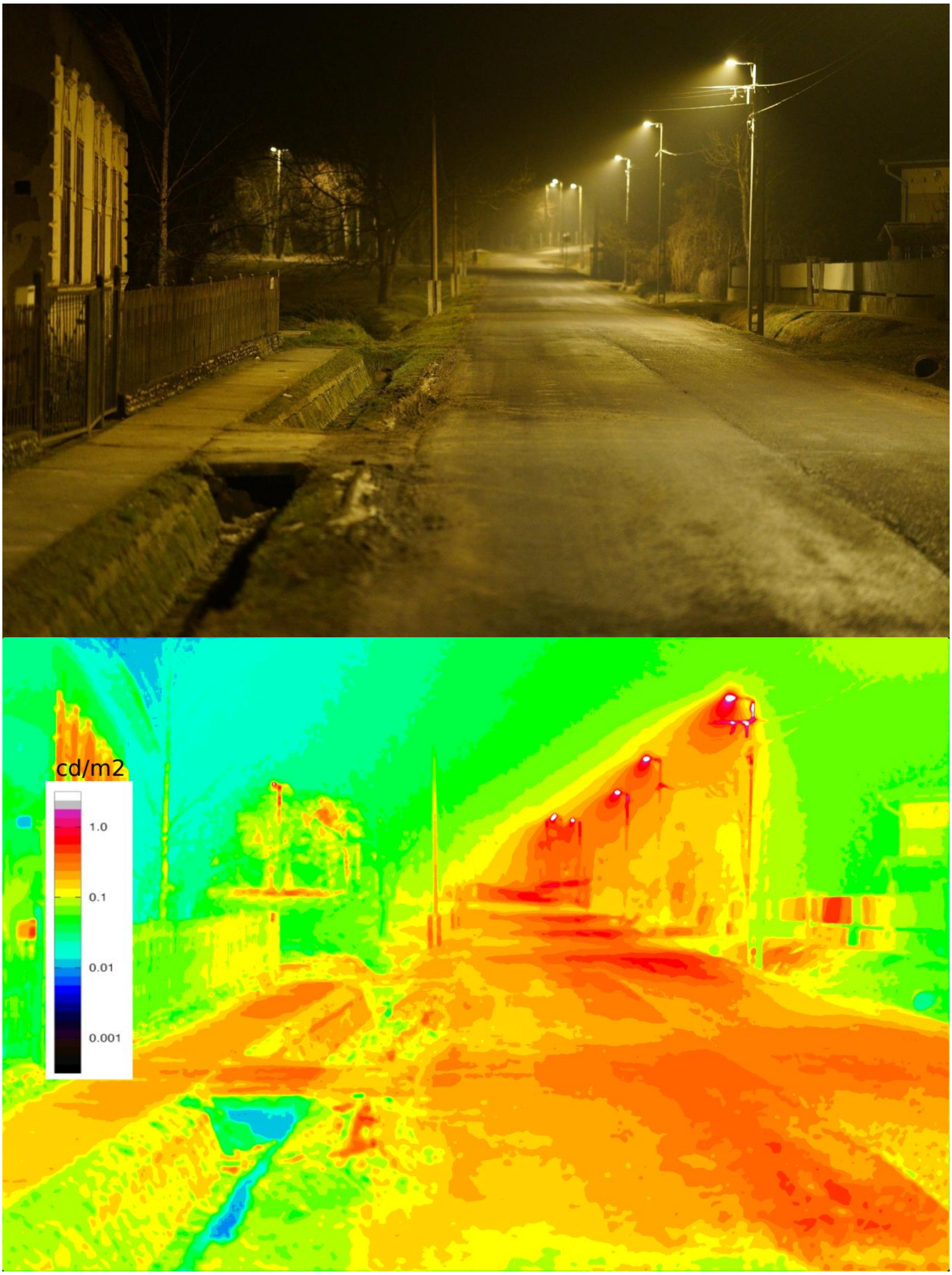

Figure 5: Photograph of the new public lighting after the public lighting reconstruction in Bárdudvarnok, Hungary (top) and the luminance map of the same street displayed with false colours (bottom). The photo was taken in foggy weather for better visualization when the backscattered luminance was higher.

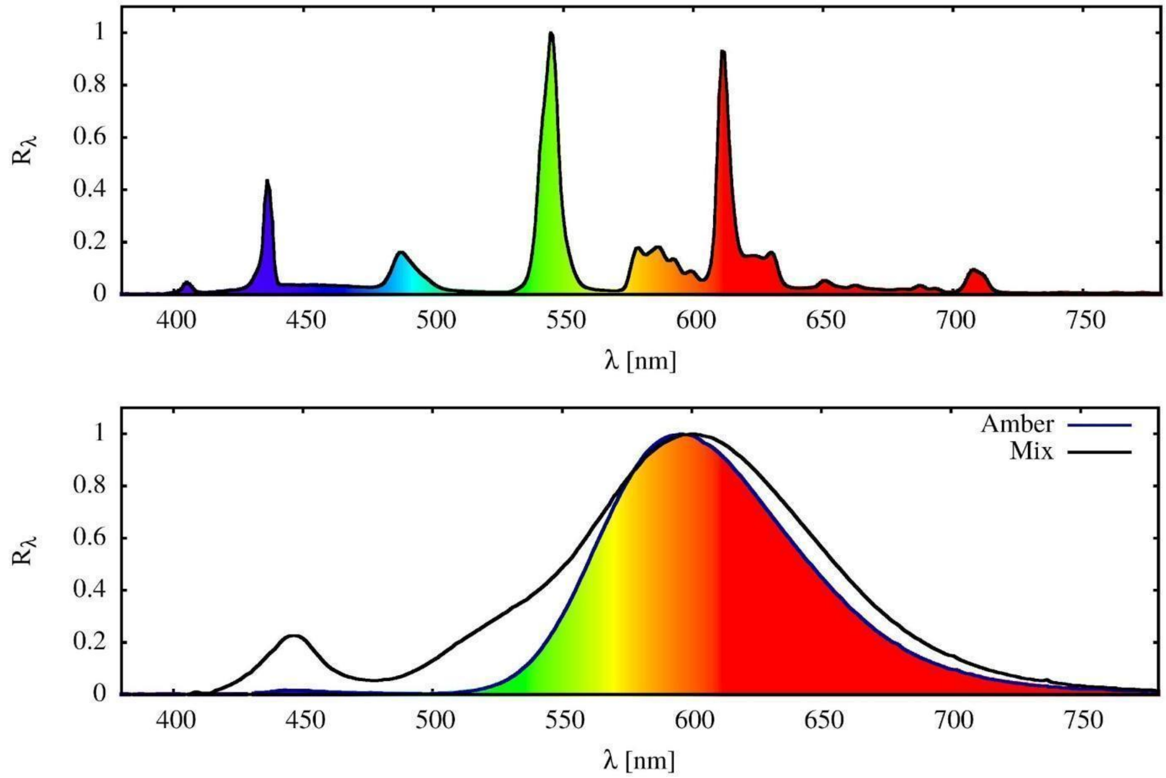

Figure 6: Spectral distribution of public lighting intensity before (top) and after (bottom) the reconstruction.

4 Discussion

The rules of IDA determine the characteristics of lighting allowed in the settlements located in the area of dark sky parks. Unfortunately, the Hungarian settlements do not fulfill these rules. We managed to construct a new public lighting system in the villages of Bárdudvarnok and Répáshuta that fulfill all these rules and as a pilot project can be a good example for lighting reconstructions in the future. Our system is unique regarding the adjustable luminous flux and spectral content of light sources that were composed of a mixture of warm white LEDs and PC amber LEDs. This system will be used as a Living Environmental Laboratory for Lighting.

The realization of LELL started with the reconstruction of public lighting. The rules of IDA determined the conditions that had to be fulfilled. Besides, we had to search for international trends and studies which provided good examples to be followed. According to one of the findings, amber light was ecologically optimal[17]. On the other hand, the applied light had to provide sufficient illuminance on the road to satisfy the public European lighting requirements according to the lighting class defined in standard EN 13201-1:2014, determined in Hungary based on the Green Public Procurement (GPP) criteria of the European Union[20].

A frequently occurring problem of public lighting is the poor orientation of lamp bodies or poorly chosen light sources, illuminating trees and buildings together with the road surface. These unnecessarily used amounts of light count as waste.[21] suggested EcoSky LEDs as an alternative choice of light sources to illuminate churches or monuments to reduce waste lighting. Since our goal was to construct a new system that fulfills the necessary requirements, reduces waste light and is suitable for scientific research at the same time, we chose to create lamps with custom design and adjustable luminous flux and spectral content.

The adjustable luminous flux and the spectral content ensures that we can perform comparative studies by using lights with different colours. One method to do this is using modern digital cameras that provide an alternative way to perform all-sky imaging either by a fisheye lens or by a mosaic image taken by a wide angle lens [22]. By measuring the luminance of the sky, we can differentiate the effect of settlements from other natural light sources, using different lighting schemes. With these comparative measurements, we can determine the extent of light pollution reduction caused by the change of public lighting in the two settlements. A standard method of differential measurements is described in detail by [23] and [24]. The results of instrumental measurements of the light pollution is comparable with previous [25] and present light pollution surveys performed in the Zselic Starry Sky Park.

Public lighting reconstructions usually raise attention and gain publicity and also critics. Similar previous projects conducted by others had different errors; for example, the new system did not provide enough light for pedestrians. Such mistakes had to be avoided: due to the flaws of the former system, the total luminous flux had to be increased. Thus, the energy consumption of the basic lighting could not be reduced. In the old system, the CFL lamps were rather old with a luminous flux of ca. 2000 lm, whereas, the total luminous flux of the new LED lamps were 4200 lm (white LEDs: 2500 lm, PC amber LEDs: 1700 lm). Since CFL lamps were poorly constructed, a large amount of their luminous flux went to the upper hemisphere, resulting in a peak illuminance of 3.4 lx (1.9 lx in average) on the ground between two lamp poles. In the new system, during early night mode (PC amber + white LEDs), the peak illuminance was 24.3 lx (13.1 lx in average) and during late night mode (only PC amber LEDs) 8.1 lx (3.9 lx in average). With this system we could ensure clear visibility on the road without using too much light.

We put high emphasis on the reactions of local people. Using the possibilities of modern information technology, we created a Facebook group to collect the opinions of the residents. Although only 23 people commented, their responses were positive; we did not get any negative critics. They mentioned the improvement of the quality of illumination and regarded the colour change as beneficial. They also mentioned that the orientation of some luminaires was not perfectly horizontal, which can be corrected later. Some observations showed the local increase of light pollution in some streets. These responses have to be checked and justified by measurements. We also made oral interviews with locals about the lighting change and got overwhelmingly positive opinions. We note however, that a detailed statistical survey is out of the scope of this paper. In general, the population considered the installation of the Living Environmental Laboratory for Lighting as a positive change.

5 Outlook

With the installed new lighting technology, we can use the new system for LELL purposes. Besides measuring the different spectral power distributions, we are planning to survey the biological effects of the applied light sources, so that we could get information about the environmentally optimal public lighting solutions. Evidences show that the circadian clock of birds nesting around human settlements have changed compared to those that are not prone to light pollution in the forests [26]. This change is induced by the alteration of melatonin production, causing an altered behaviour of daily cycles of activity/rest and timing of reproduction [27]. Nocturnal insects are also affected by night lighting. Some insect groups (e.g. moths, bees, dung beetles) are able to distinguish colors, to detect faint movements, to learn visual landmarks, to orient to the faint pattern of polarized light produced by the moon, and to navigate using the stars[28]. High intensity public illumination can lure away nocturnal and night-swarming aquatic insects from their natural habitats and if this distraction happens around a polarizing surface, like an asphalt road, most insects get trapped until they die of dehydration [29–31] Observation plans are prepared to study for example the behaviour of pollinating insects and singing birds in the presence and absence of these light sources.

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References

[1] Riegel, K. W. (1973). Outdoor lighting is a growing threat to astronomy. Science, 179, 1285-1291.
[2] Kyba, C. C. M., Ruhtz, T., Fischer, J., & Hölker, F. (2012). Red is the new black: how the colour of urban skyglow varies with cloud cover. Monthly Notices of the Royal Astronomical Society, 425(1), 701-708.
[3] Kyba, C. C., Tong, K. P., Bennie, J., Birriel, I., Birriel, J. J., Cool, A., ... & Ehlert, R. (2015). Worldwide variations in artificial skyglow. Scientific reports, 5, 8409.
[4] Longcore, T., & Rich, C. (2004). Ecological light pollution. Frontiers in Ecology and the Environment, 2(4), 191-198.
[5] Horváth, G., Kriska, G., Malik, P., & Robertson, B. (2009). Polarized light pollution: a new kind of ecological photopollution. Frontiers in Ecology and the Environment, 7(6), 317-325.
[6] International Dark-Sky Association (IDA). (2017). International Dark Sky Parks, Retrieved from https://bit.ly/358v9aZ
[7] International Dark-Sky Association (IDA). (2018). IDA International Dark Sky Park Designation Guidelines,

Retrieved from https://bit.ly/2Pzg6Az

[8] Nefedov, E., Maksimainen, M., Sierla, S., Flikkema, P., Yang, C. W., Kosonen, I., & Luttinen, T. (2014, June). Energy efficient traffic-based street lighting automation. In 2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE) (pp. 1718-1723). IEEE.

[9] Kyba, C. C., Kuester, T., De Miguel, A. S., Baugh, K., Jechow, A., Hölker, F., ... & Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. Science advances, 3(11), e1701528.

[10] Pawson, S. M., Bader, M. F., Brockerhoff, E. G., Heffernan, W. J. B., Kerr, J. L., & O'Connor, B. (2019). Quantifying the thermal tolerance of wood borers and bark beetles for the development of Joule heating as a novel phytosanitary treatment of pine logs. Journal of Pest Science, 92(1), 157-171.

[11] Ouerhani, T., Pflieger, R., Ben Messaoud, W., & Nikitenko, S. I. (2015). Spectroscopy of sonoluminescence and sonochemistry in water saturated with N2–Ar mixtures. The Journal of Physical Chemistry B, 119(52), 15885-15891.

[12] Carrino, F., Mugellini, E., Abou Khaled, O., Ouerhani, N., & Ehrensberger, J. (2016). iNUIT: Internet of things for urban innovation. Future Internet, 8(2), 18.

[13] Jeff K., (2018). Forbes. Retrieved from https://bit.ly/2sarzOW

[14] Sébastien G,. (2014), Mont-Megantic International Dark Sky Reserve. Retrieved from https://bit.ly/34d9kpy

[15] Garcia-Saenz, A., Sánchez de Miguel, A., Espinosa, A., Valentin, A., Aragonés, N., Llorca, J., ... & Tardón, A. (2018). Evaluating the association between artificial light-at-night exposure and breast and prostate cancer risk in Spain (MCC-Spain study). Environmental health perspectives, 126(4), 047011.

[16] Aubé, M., Roby, J., & Kocifaj, M. (2013). Evaluating potential spectral impacts of various artificial lights on melatonin suppression, photosynthesis, and star visibility. PloS one, 8(7), e67798.

[17] Longcore, T., Rodríguez, A., Witherington, B., Penniman, J. F., Herf, L., & Herf, M. (2018). Rapid assessment of lamp spectrum to quantify ecological effects of light at night. Journal of Experimental Zoology Part A: Ecological and Integrative Physiology, 329(8-9), 511-521.

[18] Jechow, A., Hölker, F., & Kyba, C. C. (2019). Using all-sky differential photometry to investigate how nocturnal clouds darken the night sky in rural areas. Scientific reports, 9(1), 1-14.

[19] Poppe, A., Szalai, A., & Parry, J. (2012). Advanced thermal characterization improves LED street-light design. LEDs Magazine, 9(7), 51-56.

[20] Donatello, S., Rodríguez, R., Quintero, M. G. C., JRC, O. W., Van Tichelen, P., Van, V., & Hoof, T. G. V. (2019). Revision of the EU Green Public Procurement Criteria for Road Lighting and Traffic Signals.

[21] Kyba, C. C. (2018). Is light pollution getting better or worse?. Nature Astronomy, 2(4), 267-269.

[22] Kolláth, Z., & Dömény, A. (2017). Night sky quality monitoring in existing and planned dark sky parks by digital cameras. arXiv preprint arXiv:1705.09594.

[23] Kyba, C. C. M., & Lolkema, D. E. (2012). A community standard for recording skyglow data. Astronomy & Geophysics, 53(6), 6-17.

[24] Jechow, A., Ribas, S. J., Domingo, R. C., Hölker, F., Kolláth, Z., & Kyba, C. C. (2018). Tracking the dynamics of skyglow with differential photometry using a digital camera with fisheye lens. Journal of Quantitative Spectroscopy and Radiative Transfer, 209, 212-223.

[25] Kolláth, Z. (2010, March). Measuring and modelling light pollution at the Zselic Starry Sky Park. In Journal of Physics: Conference Series (Vol. 218, No. 1, p. 012001). IOP Publishing Ltd.

[26] Dominoni, D. M., Helm, B., Lehmann, M., Dowse, H. B., & Partecke, J. (2013). Clocks for the city: circadian differences between forest and city songbirds. Proceedings of the Royal Society B: Biological Sciences, 280(1763), 20130593.

[27] Dominoni, D. M., Goymann, W., Helm, B., & Partecke, J. (2013). Urban-like night illumination reduces melatonin release in European blackbirds (Turdus merula): implications of city life for biological time-keeping of songbirds. Frontiers in zoology, 10(1), 60.

[28] Warrant, E., Oskarsson, M., & Malm, H. (2014). The remarkable visual abilities of nocturnal insects: neural principles and bioinspired night-vision algorithms. Proceedings of the IEEE, 102(10), 1411-1426.

[29] Boda, P., Horváth, G., Kriska, G., Blahó, M., & Csabai, Z. (2014). Phototaxis and polarotaxis hand in hand: night dispersal flight of aquatic insects distracted synergistically by light intensity and reflection polarization. Naturwissenschaften, 101(5), 385-395.

[30] Szaz, D., Horvath, G., Barta, A., Robertson, B. A., Farkas, A., Egri, A., ... & Kriska, G. (2015). Lamp-lit bridges as dual light-traps for the night-swarming mayfly, Ephoron virgo: interaction of polarized and unpolarized light pollution. PLoS One, 10(3), e0121194.

[31] Egri, Á., Száz, D., Farkas, A., Pereszlényi, Á., Horváth, G., & Kriska, G. (2017). Method to improve the survival of night-swarming mayflies near bridges in areas of distracting light pollution. Royal Society open science, 4(11), 171166.