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Sustainable Architectural Lighting of Historical Monuments

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Abstract. Before electric lighting, all-night facade illumination was technologically and economically unfeasible, limiting designs to natural daylighting. In the 21st century, night-time electric lighting enhances building aesthetics and is essential for historical monuments, altering the night-time urban landscape and increasing light pollution. This study analyses the current lighting of Vyšehrad in Prague, using luminance analysis and spectral measurements to assess visual appearance and less visible impacts like light pollution and nighttime disruption. The findings underscore the need for sustainable architectural lighting practices. A virtual model suggests modifications to reduce environmental impact while preserving the aesthetic and historic value of illuminated monuments.

1. Introduction

Architectural lighting of historical buildings plays a key role in shaping the atmosphere of the nighttime urban environment. Its primary purpose is to highlight the aesthetic and cultural value of monuments [1], while also influencing the perception of architectural details and the overall visual composition of the city. With the advancement of technology, nighttime lighting has become a common feature of public spaces; however, discussions about its visual and mainly environmental impacts are increasing among scientists [2] as well as state administrations [3]. In 2023, the Czech Republic introduced a technical standard setting limits for outdoor lighting to reduce the disruptive effects of artificial light on the surroundings [4]. However, specific methodological guidelines for the architectural lighting of historically protected buildings are still insufficiently developed.

Original historical buildings were designed exclusively for natural daylight, which was reflected in their color and material appearance and shaped their plasticity through the natural play of light and shadow. With the advent of powerful electric light sources, artificial lighting has been increasingly used to enhance the visibility of monuments, fundamentally transforming the nighttime landscape. Modern LED based lighting technology allows for dynamic manipulation of light and its hue [5], which significantly changes the appearance of objects under heritage protection. It also raises concerns related to excessive lighting intensity, which causes over-illumination of objects, high contrast between illuminated and non-illuminated surfaces, and potential glare.

Use of powerful light sources, with high short-wavelength (blue light) proportion, and frequent upward direction of light beams, particularly in architectural lighting, results in illumination of areas beyond the intended surface. The light pollution, with an estimated global increase of 3–6% per year, which over a decade corresponds to a 35–80% increase [6], causes not only reduces the visibility of the night sky, but also contributes to ecosystem disruption. It affects biodiversity, disorients nocturnal animals [7], and disrupts the human circadian rhythm [8]. These photobiological effects should be expressed with respect to physiology. The standard parameter of light technology, the Correlated Color Temperature (CCT), is not a reliable predictor of biological activity [9].

The biological impact of light on humans is already reasonably well described and can be expressed by the Melanopic Daylight Equivalent Ratio (MDER) [10] parameter, based on the spectral sensitivity of the human eye. For night-time illumination, MDER value is recommended to be kept as low as possible, optimally bellow 0,3. Determining the effect of light across other wildlife species is significantly more challenging. A new parameter, denoted U500 [11], is being introduced to reflect the representation of light energy in the most sensitive region for wildlife, i.e. the percentage of emitted light with a wavelength below 500 nm. Higher U500 values are associated with an increased biological impact on ecosystems. The methodology currently being finalised by the Ministry of the Environment of the Czech Republic defines a maximum U500 ranging from 12% in city centres to 1% in protected natural areas.

2. Study design

This study presents an analysis of the architectural lighting of Vyšehrad, an important historical district in Prague, Czech Republic. The goal of the study is to achieve a balance between aesthetic requirements, heritage conservation, energy consumption, and minimizing light pollution and other negative effects on nocturnal wildlife, i.e. ensuring that the architectural lighting in the historical site complies with the principles of sustainability.

The Vyšehrad National Cultural Monument is located on a rocky promontory above the Vltava River. Originated in the 10th century, this historic fortress is an important part of the Prague Heritage Reservation and is one of the key landmarks in the city's nighttime panorama. The area also serves as an important urban greenery. The most significant illuminated structures are the Basilica of St. Peter and Paul, the Rotunda of St. Martin, and the baroque fortification walls and gates.

In the first step, the critical analysis of the current lighting in the area identifies key factors that affect visual and esthetic quality and environmental effects that may impact sustainability. Following case study proposes concepts of lighting optimization for a specific building (Rotunda of St. Martin) are presented using the virtual twin model.

For the site analyses, subjective and objective (luminance analysis) methods are used to evaluate the lighting in a historical context, particularly to identify how specific parameters of LED light sources contribute to the visual experience and perception of historical structures.

The objective measurements of the illuminated environment used luminance analysis Luminance Distribution Analyzer (LDA) with a wide-angle lens, calibrated for human spectral sensitivity. This analysis was performed in multiple key viewpoints in the site. The produced HDRI images, analysed in LumiDISP software, were used to calculate luminance contrast and uniformity at the surface, to identify glare risks and light penetrating outside the target area. Spectral measurements were conducted with calibrated spectroradiometer UPRTEK to analyse the spectral composition of light sources. Data were processed in Luoxtech [12] to assess the proportion of short-wavelength components and calculate the MDER and U500 coefficients and quantify the potential impact on wildlife.

Evaluation of the aesthetic impact of the current lighting system was done using subjective on-site evaluation via interviews with experts and casual observers about their subjective preferences, glare or visual discomfort one hour after sunset. As a part of the experiment, some parameters of the current lighting (luminous flux, hue and directionality) were adjusted based on visitors' comments and their feedback was observed.

A virtual twin of the Rotunda of St. Martin was created in the lighting design software DIALux to evaluate the lighting system for three scenarios: "Current Lighting", "Basic Replacement" and "Dim & Detail Lighting". Next to the photorealistic image, the virtual model also calculated luminance level and distribution on the building façade, the total amount of light used, the spill light emission towards the sky, as well as energy and operational parameters. The results provided a comparison of the efficiency of each scenario, identifying the optimal solution in terms of aesthetic quality, sustainability, and minimizing unnecessary light emissions.

3. Results

The critical analysis of the current lighting assessed visual appearance, energy consumption and effects of spectral composition on wildlife in the night environment. Several parameters have been identified as the key factors affecting the quality of the lighting environment.

3.1 Excessive brightness causing high contrasts

Purpose of architectural lighting is to draw attention to important structures and support their visual appearance. Brightly lit volume of St Martin's Rotunda contrasts strongly with its darker surroundings (Fig. 1), with the façade median luminance of 2 cd/m^2, which is 100 times higher than the background. This is beyond the eye's ability to adapt to darkness and makes it difficult to navigate in the night environment. Also, bright hotspot is visible to the naked eye on one side of the rotunda. Measurements confirmed poor illumination uniformity (contrast exceeding 10:1).

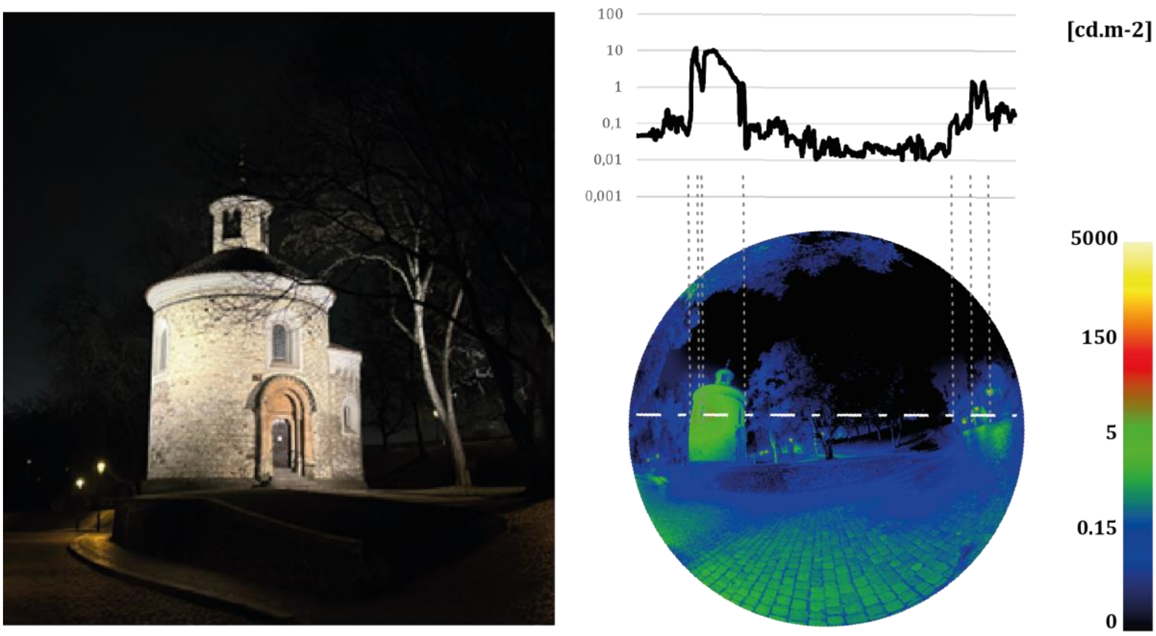

Figure 1. Photo of the current state of lighting of the St. Martin's Rotunda with luminance analysis (luminance profile)

In contrary to its purpose, lighting of the Basilica of Saints Peter and Paul is most prominent on its side façade, where the brightness (8.3 $cd.m^{-2}$) is four times higher than that of the basilica main portal (1 $cd.m^{-2}$). Not only the levels close to the acceptable limits [4], but also visitor's attention is directed away from the significant parts to less important areas. Further, strong contrast transitions between illuminated surfaces and darkness in the surrounding park can cause visual discomfort for visitors, particularly when approaching the basilica from south, where the measured façade brightness is more than 150 times higher than the background luminance. These examples illustrate that the brightness on façades often exceeds the level necessary for proper visual perception and can be significantly reduced. Further, choosing too high luminance levels not only reduces visual comfort, disrupts the nighttime ambiance of the historical site but also increases the lighting energy consumption.

3.2 Visual delight in historical context

On-site observations confirmed that the light sources installed for local architectural lighting operate at higher correlated color temperatures (CCT) than the traditional fire-based ones, which produced a warm, yellowish, flickering light that is more natural for nighttime environments. The appearance of details originally designed to be lit by daylight, with light falling from above in the sky, can be also affected by the direction of the electric light, which casts the shades differently, reducing the legibility of the architectural details and distorting the original sculptural effect.

Interviews performed with experts and casual observers (n=17) was used to validate findings on the objective measurements. Although the perception of light is significantly dependent on the material being illuminated, interviews confirmed that the luminance of surfaces can be significantly reduced, warmer light is more pleasant and perceived as better to the genius loci of the heritage site, while the installed metal-halide lighting resembles cool, white daylight. Furthermore, luminaires installed at pavement level can cause discomfort glare.

As part of a field experiment, ground-recessed luminaires (Fig. 2) were partially shielded. Their lack of adequate glare control causes discomfort for pedestrians. Respondents stated that after shading the fixtures, the plasticity of the façade was enhanced, and architectural details became more legible due to the reintroduction of shadows. The shaded section appeared more pleasant and aesthetically appealing. A possible solution is to equip these luminaires with shields or grilles or to reduce the illumination intensity.

A well-designed lighting concept that integrates lower CCT, appropriate intensity, and precise light direction not only enhances the aesthetic quality of illumination but also reduces light pollution and ensures better harmony with the nighttime character of historical monuments.

Figure 2. Main façade of the basilica. Light at the right portal are partially shielded during the perception experiment.

3.3 Light directed outside the target area

The upward directed light beam is specific to architectural lighting to provide illumination of vertical structures such as basilica towers or fortification walls (Fig. 3). Due to inaccurate directionality, vertically projected light illuminates the night sky and can contribute to light pollution over distances of numerous kilometres. In this case, it excessively brightens the night sky over Prague, reducing the visibility of the stars and disturbing the natural night-time character of the city. Furthermore, light spilling upwards along the wall can cause a risk of dazzle and dizziness for visitors if they lean over the edge of the wall. It creates strong, intrusive illumination of surrounding vegetation. These undesirable effects can be mitigated by appropriate design of the lighting system, in particular the addition of precise shielding of light sources.

Figure 3. Light spill visible above the basilica (left) and the fortification walls of Vyšehrad (right).

3.4 Effect of light on living species

Mix of various lighting technologies is installed in the Vyšehrad area. Majority of the architectural lights use the metal-halide technology, public lighting is installed in high pressure sodium (HPS). Fig. 4 shows spectral composition of these light sources in comparison to examples of new technologies such as warm LED (2200 K), warm/neutral LED (3000 K) and PC Amber LED, used as a replacement for HPS lights.

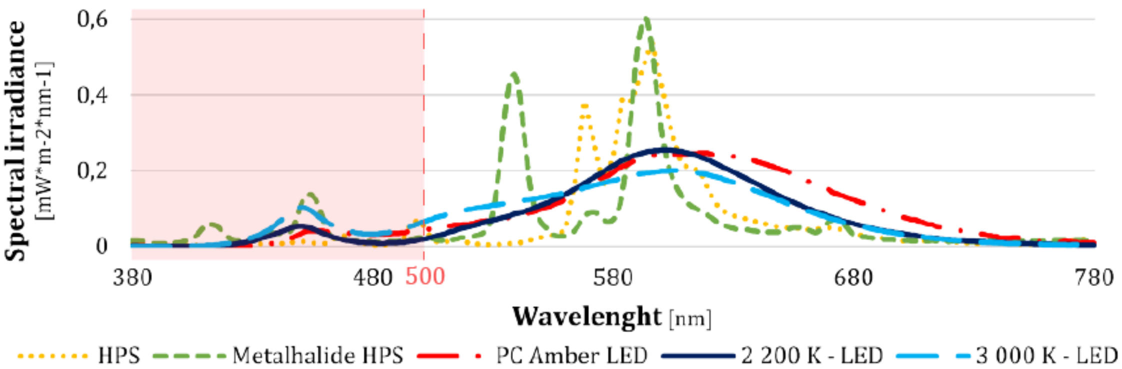

Figure 4. Comparison of spectral characteristics of selected sources

Spectral composition affects not only the appearance of illuminated surfaces, but the proportion of wavelengths < 500 nm is crucial for daily and seasonal synchronization of biological processes of the living organisms. During the night this part of spectra need to be limited and this is particularly important in areas directly interacting with natural elements, where electric lighting can disrupt the biological balance of the environment. The comparison of light sources with calculated effects on human and wildlife through MDER and U500 see in Table 1.

Table 1. Comparison of CCT, Melanopic EDI, and U500 of selected sources

	High pressure sodium (HPS)	Metalhalide HPS	PC Amber LED	2200 K LED	3000 K LED
CCT [K]	1900	3130	2150	2200	3000
MDER [-]	0.1328	0.3384	0.2924	0.2325	0.4530
U500 [%]	4.9	14.1	5.8	6.1	13.5

4. Case study – New architectural lighting of St. Martin's Rotunda

Optimalization of the architectural lighting has been tested using the virtual twin model of the Rotunda of St. Martin. The current setup and 2 suggested scenarios were investigated, see Fig. 5.

Scenario 1 – Current State
Current lighting consists of 6 high-power metal halide luminaires. The luminance on the surface is uneven and the building is significantly over-lit relative to its surroundings. The luminous flux is not shielded to target solely the object, resulting in a risk of glare and reduced visual comfort for pedestrians. The high light dispersion also affects the surrounding environment and disturbs the night-time atmosphere of the historic site. The virtual model also confirms that a significant amount of light is directed towards the sky (4.49 lx), increasing light pollution.

Scenario 2 – Basic Replacement
The scenario presents a cost-effective solution by maintaining the existing light positions and switching from the existing sources to three 41W LED luminaires. By using the correctly chosen optics, the lighting becomes more controlled and uniform. Installing lower light output will eliminate over-lighting of the building, reduce the risk of glare, and improve visual comfort and perception of architectural details. Improved directivity of light (upward light emission of 1.18 lx) preserves the nocturnal character of the environment, making the site less intrusive in the urban landscape.

Scenario 3 – Dim & Detail Lighting
This scenario primarily uses existing interior lighting sensitively supplemented by 3 LED sources. The interior lighting allows the light to diffuse through the architectural openings and non-violently define the structure of the building. Two 8W exterior luminaires provide focused accent lighting for the entrance portal, while a 30W luminaire highlights the lantern and contributes to the spatial perception. Minimal upward light emission (0.45 lx) significantly reduces light pollution, preserving the nighttime environment while maintaining adequate visibility of major architectural elements and supporting historical value of the building.

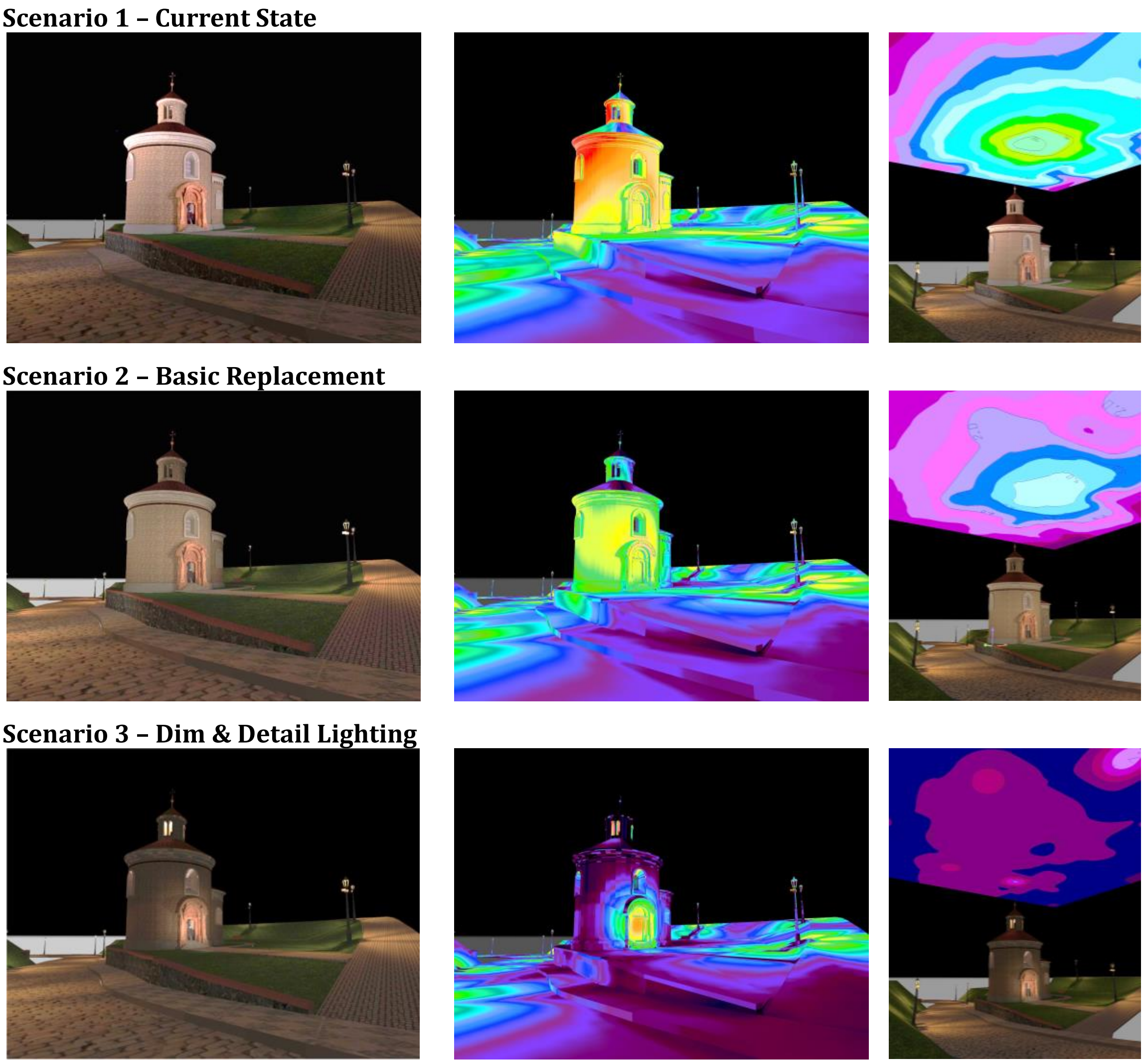

Figure 5. Virtual model of Scenarios – realistic rendering (left) and luminance distribution calculation (middle) and upward light emission view (right)

Table 2. Comparison of Energy Consumption and Light Emission in Different Scenarios

Scenario	Number of luminaires and outputs	Maximum values of upward light emission [lx] [a]	Energy consumption [kWh/year] [b]	Operating cost [€/year] [c]	Energy savings [%]
1	2x 150W +4x 70W	4.49	1137.6	193.4	0
2	3x 41W	1.18	194.34	33.0	83
3	2x 8W +1x 30W	0.45	72.68	12.4	94

[a] Measured at a height of 25 m above the ground
[b] The hours of light within the year are set in the mode from dusk to CEST midnight (1580 hours in total)
[c] 0.17 €/kWh (based on energy prices in January 2025)

5. Conclusion

The study highlights the importance of multidisciplinary design approach in order to achieve sustainable and functional results. While effective illumination can enhance the visual and cultural appreciation of historical landmarks, improper lighting strategies often contribute to excessive brightness, high luminance contrast, and significant light pollution. The presence of uncontrolled light direction and excessive illuminance, particularly in areas exceeding the U500 threshold, further exacerbates these issues.

Findings from our research demonstrate that mitigating negative effects can be achieved through smart design lighting. Lower correlated colour temperatures (CCT) and precise directional control of light sources represent a significant tool in reducing adverse impacts. Additionally, the integration of interior illumination with targeted shielding enhances sustainability while preserving the site's visual integrity. Optimization of lighting design through smart solutions reduces light pollution, offering a model for future applications.

The analysis highlights the potential of precise design to address critical lighting challenges. By respecting the natural landscape and genius loci of historic monuments, sustainable lighting strategies can be seamlessly integrated into the urban environment. The case study confirms that through technology-driven solutions, it is possible to reconcile modern lighting requirements with historic preservation and environmental responsibility.

Upcoming research should address dynamic lighting control, spectral tuning and interdisciplinary collaboration to advance sustainable urban lighting. These innovations will further refine approaches to responsible lighting and ensure that historic landmarks remain visually appealing while minimizing ecological and environmental footprints.

Acknowledgements

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