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Light pollution – not just an energy problem

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Abstract

Light pollution is a growing problem in developed countries. One of its categories, often associated with this concept, is night sky glow. This glow is caused by scattering light from artificial ground light sources on atmospheric particles. The paper indicates that street lighting may be the primary source of light scattered on these particles. This is caused by often outdated luminaires or their installation, which does not protect the surroundings from light pollution. The second, even more important factor increasing the brightness of the sky glow may be the reflection of incident light upwards by the street surface. Satellite images of the Earth's surface allow for determining the radiance from a given area, determined by the amount of light scattered in the atmosphere. However, the part of this light associated with street lighting is difficult to separate from the background of other artificial ground light sources. In 2020, due to the COVID-19 pandemic and reduced traffic at night, the authorities of several municipalities in the Małopolska province in Poland decided to switch off street lighting at night. This was the first time street lighting was switched off for part of the year in large areas and entire cities. Analysis of satellite data allowed us to determine that the luminance from the analysed localities decreased by almost 70% after switching off city lighting. The analysis also allowed us to estimate the energy losses of city lighting resulting from lighting fixtures that do not protect the surroundings from light pollution.

Keywords: Light pollution; Radiance; Artificial sky glow; Street lighting; Energy loss

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1. Introduction

1.1. The history of the problem

At the end of the 19th century, it was noticed that city street lighting was the leading cause of the formation of the night sky glow, which hurts the quality of astronomical observations [1,2]. Of course, many natural light sources brighten the night sky (the Moon, planets, stars, etc.) [3], but the anthropogenic component always dominates in urban conditions. This is why the term "light pollution" is often treated as synonymous with the artificial glow of the night sky. The observation of the effect of city street lighting on brightening the night sky led to light pollution in the form of the artificial night sky glow being treated as another example of human pollution of the natural environment. Initially, it was important only for astronomers. Until the beginning of the 20th century, astronomical observatories (Greenwich, Mt Wilson, Mt Palomar, Kraków-Botanical Garden) were located on the outskirts of cities, most often university centres, which were dictated by logistical reasons. Modernising urban lighting, especially its electrification, meant that these observatories were frequently moved to new locations, far from civilisation (Hawaii, the Canary Islands, Czarnohora) [4,5]. Starting mainly from the end of the 20th century, other light sources have

Nomenclature

L – radiance, nW/(cm^2·sr)

Abbreviations and Acronyms

BREEAM – building research establishment environmental assessment method
CCT – correlated colour temperature
CO – commune office
DNB – day/night band
ISS – international space station
LAADS DAAC – Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center
LPTT – Light Pollution Think Tank
NOAA – National Oceanic and Atmospheric Administration
PCA – principal component analysis
SQM – sky quality meter
ULOR – upper light output ratio
UM – City Office
UMiG – City and Commune Office
VIIRS – visible infrared imaging radiometer suite

significantly contributed to brightening the sky: illuminated advertisements, lighting of sports facilities, monuments, parking spaces or commercial facilities, etc. [6−10]. These and other light sources make cities the primary source of light pollution in the night sky.

The sky glow is caused by light scattering on aerosols and atmospheric molecules. Light scattered in this way also affects the environment further away from the cities that are its source. To determine the potential impact of such scattered light on the surroundings of cities, several theoretical models have been developed to describe the distribution of night sky brightness in these areas. Walker created the first simple models in the 1970s based on data on population density [11−13]. The basic model describing the effect of cities on the night sky brightness was developed in 1973 by Treanor [14] and then improved in 1976 by Berry [15]. Based on these models, the Garstang model [16−18] was developed, which is still used today and is still being developed by correlating with measurement data. Currently, the most commonly used model of city light scattering on various types of atmospheric aerosols is Illumina [19], a new improved version of which was published in September 2020 [20]. Since 1972, it has been possible to quantitatively analyse light emissions from cities (radiance) based on satellite images taken by the Defense Meteorological Satellite Program (DMSP) satellites. DMSP images were used to verify the correctness of the previously mentioned models [21,22], which enabled the development of an atlas showing the model distribution of the brightness of the night, cloudless sky, observed from the ground (The First World Atlas of the Artificial Night Sky Brightness) [23].

The emergence of cheap sky brightness meters such as Sky Quality Meter (SQM) has facilitated field measurements and enabled the measurement of overcast sky brightness, which is especially important from an ecological perspective. Measurement campaigns based on SQM meters were conducted in the Zselic Landscape Protection Area in Hungary in 2007−2010 [24], in Hong Kong and its surroundings in 2008−2009 [25] and 2010−2013 [26], and in Kraków and its environs in 2008−2010 [27−29], in the latter case by the team of the Light Pollution Monitoring Laboratory (LPML) operating at the Kraków University of Technology.

In 2011, the Suomi National Polar-orbiting Partnership (SNPP) satellite was launched into Earth's orbit [30]. The satellite, made by the US National Oceanic and Atmospheric Administration (NOAA), carried the visible infrared imaging radiometer suite (VIIRS) camera. The ground resolution of cameras on previous DMSP series satellites was 3 km, while in the case of VIIRS, it is only a few hundred meters [31]. Images taken in the day/night band (DNB) allow for determining the radiance from a given area (wavelength 0.7 µm), both coming directly from light sources and reflected from the ground [32]. VIIRS data were also used to create an artificial sky glow model [33] and a new atlas of the night sky brightness [34].

Night photos of cities (Warsaw, Kraków) taken by astronauts staying on the International Space Station (ISS) allow for categorising the types of urban lighting used (Fig. 1) [35].

Fig. 1. Night photograph of the city centre of Kraków (Poland) taken from the International Space Station on March 28, 2017 [35].

These images can distinguish all types of communication routes and, based on differences in their colours, identify areas where metal halide or high-pressure sodium (HPS) lighting has been replaced by LED lighting.

1.2. Street lighting as a source of light pollution

The impact of street lighting in cities on the brightness of the artificial sky glow and on the environment has been known for a long time [36−40]. Many attempts have been made to determine the contribution of particular types of urban lighting to the brightness of the night sky's glow. The assessment of this contribution is facilitated by local shutdowns of part or all of the municipal lighting. Analysis of the total radiance of Flagstaff (Arizona, USA) conducted in 2009 showed that about 8.3% of the city light "escapes" into space, of which 33% comes from the lighting of sports facilities. After excluding this type of lighting, commercial and industrial lighting constituted 62%, residential lighting 14%, and road lighting 12% [41]. A similar analysis was conducted in 2006 for Reykjavik (Iceland), where all street lighting was switched off for several minutes in connection with the preparations for the International Film Festival [42]. It was only found that street lighting significantly contributes to light pollution of the night sky. In 2019, an experiment was conducted in Tucson (Arizona, USA) to obtain information about the share of light emission from street lighting and private property lighting. Additionally, the related energy consumption was estimated. The intensity of street lighting was deliberately changed for 10 days, and during this time, the change in satellite radiance was studied. It was found that municipal street lighting was responsible for only 13% of the total radiance emitted from the Tucson area after midnight [43]. When this lighting was not switched off, its contribution to the total radiance was determined to be 18%. When street lighting operated by other suppliers was considered, these values increased to 16% and 21%, respectively. Simultaneous measurements of the zenith brightness of the sky during this period, when the power for street lighting decreased from 90% before midnight to 30% after midnight, showed that the brightness decreased by 5.4% near the city centre and 3.6% in the adjacent, suburban location [44]. The light source distribution model, assuming that 26% are street lamps and 74% other sources, suggests that street lamps contribute about 14% to the light emission into the sky, causing the formation of a sky glow over the city. Direct measurements, however, suggested that the contribution of street lighting to the zenithal sky brightness is only 2−3% [43]. The difference between the modelled and experimentally determined values was explained by an underestimation of the total light emission in the city, which did not take into account the changing numbers of light sources emitting light horizontally, such as indoor lighting of residential premises and others, emitting light through uncovered building windows, car headlights or illuminated road signs and advertisements. This difference may also be related to the level of air pollution in the studied areas with suspended particulate matter [45,46].

The declaration of the COVID-19 pandemic in 2020 resulted in an increased burden on healthcare, reduced population mobility and a related decline in tourism, as well as various unexpected effects on the natural environment [47]. As a result of the reduction in transport and industrial activity, the overall carbon dioxide emission decreased [48]. Improvements in air quality and reduced water pollution were also noted in many cities worldwide [49]. The effect of the pandemic was also visible through the reduction of anthropogenic seismic noise (vibrations of the ground) from train traffic, aircraft, industrial processes, etc. [50]. To limit population mobility and thus prevent virus transmission, municipal lighting shutdowns were also introduced in many European cities, which provided an unprecedented opportunity to study the effect of this type of lighting on the radiance and the brightness of the night sky glow. Studies taking into account both ground-based measurements of the sky glow brightness and satellite radiance values, performed from March 14 to May 31, 2020, for Granada (Spain), showed a significant reduction in light pollution related both to a decrease in light emissions from the city area and to the reduction in the content of anthropogenic aerosols in the atmosphere, which are the source of light scattering [45].

In 2019, a photometric map of the distribution of artificial sky glow was developed for Berlin and its surroundings, both in cloudless and overcast skies [46]. This map shows that during the pandemic, the sky's brightness at its zenith dropped by 20% in the city centre and by more than 50% at a distance of 58 km from it. At the same time, based on satellite data, it was found that the radiance from this area increased. It was suggested that the main reason for the reduction in the artificial sky glow brightness is the improvement in air quality due to the decrease in air and road traffic.

A similar analysis was conducted for several communes in the Małopolskie Voivodeship [50,51]. It aimed to research the impact of street lighting reduction on the radiance emitted from a given area with a variable degree of urbanisation. It was found that in the case of poorly urbanised communes, changes in radiance are caused exclusively by switching off street lighting in rural areas. However, in the case of urban communes, such changes are caused primarily by switching off city lighting. It was also found that switching off local road lighting is mainly responsible for reducing radiance, perhaps due to the poorer quality of lamp fittings on these streets.

In April 2020 and the following months, the authorities of Kraków, as well as several other municipalities in the Małopolskie Voivodeship, adopted a law to entirely or partially switch off street lighting during night hours, starting from midnight (or from 1:00 CEST - Central European Summer Time) until dawn (Fig. 2).

Fig. 2. Switching off street lights in Kraków. Photos were taken 12 minutes before midnight (left, a) and 15 minutes after midnight (right, b) on the night of April 26-27, 2020. The only light sources still active were a gas station (left), windows of several apartments, security lighting and advertisements (in the distance) [Photo: Author].

This allowed us to investigate the contribution of this type of lighting both to the radiance of the entire city and to the changes in the surface brightness of the night sky. This was facilitated because the VIIRS/DNB images of the study area were acquired after 1:00 CEST, i.e. after the street lights had been switched off. The subject of this publication is an attempt to determine what part of the energy emitted into the sky comes from municipal street lighting.

1.3. Impact of artificial lighting on ecosystems and human health

Artificial light at night (ALAN) introduces several disturbances in the functioning of the natural environment and is harmful to human health. The literature devoted to this issue is very abundant [52].

In particular, the following negative impacts of light pollution on the environment can be mentioned, which are especially important in the urban environment:

- disturbance of nocturnal bird migration by city lights [53],
- collision of nocturnal birds with bright office windows [54],
- disturbance of reproductive cycles of several insect species [55],
- disturbance of the hunter-prey balance in various environments, including water bodies on the outskirts of cities [56].

Night lighting also affects human health by inhibiting the pineal gland's production of melatonin. It leads to an increased risk of developing sleep disorders [57], a number of mental illnesses [58], and somatic diseases, including some cancers [59].

Given the negative impact of night lighting on humans, it is all the more important to ensure proper light emission in cities, especially in housing estates, which are currently the "bedrooms" for millions of people in Poland.

1.4. Legal regulations and standards

1.4.1. Standards specifying street lighting

The basic lighting requirements for roads intended mainly for motor traffic at high and medium speeds are based on criteria related to the level and uniformity of the luminance of the road itself, the lighting of its immediate surroundings and the appropriate limitation of glare. These criteria correspond to the relevant classes. When analysing street lighting in cities, it is necessary to consider primarily such spaces as municipal streets, residential streets, and pavements. The situation of each space mentioned above is regulated by the appropriate guidelines of the lighting standard PN-EN 13201:2016 concerning road lighting [60,61]. By this standard, classes M, C and P have been established. Class M concerns streets with increased motor traffic [62]. It concerns the area planned for motor traffic while pedestrian traffic occurs in specially designated, separate zones. Both traffic areas are treated as separate traffic zones, subject to different legal conditions. Class C concerns conflict areas, where car traffic meets pedestrian and cyclist traffic. These are areas particularly prone to collisions, which makes them dangerous and requires special solutions. This class also includes pedestrian crossings, intersections and areas with variable geometry. Class P was created mainly for road areas where pedestrians and cyclists move. Car traffic is limited in this zone, and drivers must maintain low speeds.

The requirements for street and sidewalk lighting in individual classes are limited only to the level of average illuminance and uniformity of illuminance. In particular, low-power street luminaires (usually P4 or P5 class) can be used to illuminate residential roads and sidewalks, which, when the appropriate distance between poles of 3-4 m high is maintained, illuminate the surface of sidewalks or residential streets very well, ensuring compliance with the requirements of the standard mentioned above [63]. For streets running near housing estates, the M classes apply, which include requirements for routes with higher motorised traffic [62].

All the listed classes of street lighting, regulated by the standard mentioned above, only define the minimum level of luminance on the street surface and its uniform distribution without regulating the escape of light to the surroundings. In particular, they do not define the ULOR (Upper Light Output Ratio) parameter, which specifies the percentage of light sent to the upper hemisphere, and therefore to the sky, when the lighting fixture is set horizontally to the ground (without tilt).

However, it should be remembered that street lighting should not be burdensome for the surroundings, i.e. it cannot be a source of light pollution. In particular, it should not illuminate adjacent areas, especially windows of nearby buildings (trespass effect), and it should not blind drivers and passers-by (glare effect). Incorrect design of luminaires and/or their installation may also contribute to the night sky glow generated by the city [9,64–66].

1.4.2. Standards determining the level of light pollution

In some countries, the adverse effects of artificial night lighting on the environment have been noticed. In these countries, various actions have been taken, from legal regulations on a national, regional, or local scale to the formulation of technical standards for correct lighting parameters to guide educating the general public. Supported by researchers and reports on the risks associated with artificial light at night, governments and citizens are beginning to realise that the effects of light pollution are widespread and intervention is desirable. In Poland, an example of such grassroots actions is the establishment of the Light Pollution Think Tank (LPTT), which published a multidisciplinary guide on this issue in 2022 [67] and a report on the state of light pollution in Poland in 2023 [68].

In 2022, a review of the state of knowledge about light pollution in various European countries and the measures taken against it was published [69]. In some countries, legal acts at the national level (France, Croatia) or regional level (Spain) establish the principles of protection against light pollution. In other countries (Slovenia), decrees are issued for this purpose. In a few countries, there are (Austria) or are planned (Czech Republic) technical standards regulating the selection of luminaires with parameters for reducing scattered light, choosing the correct correlated colour temperature (CCT) or others. However, these are non-binding documents, which only legal documents refer to, making the standard mandatory.

Most European countries are already taking action to address light pollution at the national level. These include regulations, strategies, technical standards, voluntary actions aimed at awareness-raising manuals or guidelines, research projects or dark sky areas.

Furthermore, light pollution is starting to be addressed at the European level, not only from an energy efficiency perspective but also from the perspective of its adverse impacts on human health and biodiversity.

A voluntary Green Public Procurement Criteria for Street Lighting and Traffic Signals, issued in 2018 and updated in 2019, guides public policymakers and lighting professionals to procure lighting equipment based on technical criteria for the design, installation and operation phases [70]. Light pollution is cited as one of the three main environmental impacts of street lighting and traffic signals, alongside energy consumption and durability. Criteria proposed to reduce energy consumption (such as dimming during low road use and selecting the lowest necessary road lighting class to prevent unnecessary over-lighting) also help reduce light pollution, along with criteria to control up and down light output factors, CCT and blue light output. The document introduces the requirement to set lighting at ALARA levels (as low as reasonably achievable), which comply with the standard class EN 13201 (Road Lighting Standards) and do not endanger road safety.

In the Zero Pollution Action Plan, a key element of the European Green Deal adopted by the European Commission in 2021, light pollution is identified as a pollutant of emerging concern and research on it will be supported by the Horizon Europe programme [71]. Pollutants of emerging concern, including light pollution, will be included in the emerging pollutant monitoring and forward-looking framework and thus translated into policy recommendations – EU criteria for green public procurement of road lighting and traffic signals.

The impact of light pollution on ecosystems has also been noted. In particular, light pollution has been mentioned as one of the factors of pollinator decline, which will be addressed in the revised EU Pollinator Initiative [72].

In the document [69], the legislation, standards and manuals published in each of the 27 European Union countries, as well as in the United Kingdom and the EFTA states (Iceland, Liechtenstein, Norway and Switzerland), were analysed. Poland is listed and described as a country without a national policy on light pollution. However, there are awareness-raising initiatives connected to light pollution, in particular, the activities of the LPTT or the parks and dark sky protection areas operating in Poland. The aforementioned PN-EN 13201:2016 standard does not constitute legal regulations. Moreover, as already stated, it only describes the lighting of road surfaces, saying nothing about reducing light pollution.

Environmental protection issues in Poland are specified in the Environmental Protection Law (Dz.U., 2022, 2556). According to its provisions, ecological protection means taking or omitting actions that enable maintaining or restoring natural balance. On the other hand, the Act defines "pollution" as an emission that may be harmful to human health or the state of the environment, may cause damage to material goods, may deteriorate the aesthetic values of the environment or may interfere with other, justified ways of using the environment. The above definition could also include light pollution. The consequences of omitting light in the Environmental Protection Law are significant. Light emissions have not been assigned reference measurement methods or emission standards, which makes it challenging to monitor the intensity of artificial light effectively. Since there is no "emission standard", it is impossible to determine if it has been exceeded. Therefore, any emission of artificial light, regardless of intensity, cannot be considered pollution under the law.

The qualification of light as a possible environmental pollution is unambiguous in European Union legislation. Directive 2011/92/EU of the European Parliament of 2011 obliges Member States to prepare an environmental impact assessment of specific investments (in Polish regulations, their nature is specified in the rules on projects that may significantly impact the environment). The directive speaks directly about assessing the type and quantity of expected residues and emissions (water, air and soil pollution, noise, vibrations, light, heat, radiation, etc.) resulting from the operation of the proposed project. Light is mentioned here alongside radiation.

The provision mentioned above was introduced into the legislation of the European Union in 1985 by Council Directive 85/337/EEC (OJ L 175, 5.7.1985, p. 40) and was retained in later legislative amendments. The implementation of the directive in Poland took place through the Act of 3 October 2008, which provided information on the environment and its protection, public participation in environmental protection, and environmental impact assessments (Dz.U. 2023, item 1094, as amended).

However, Polish legislation does not list a catalogue of possible forms of pollution like the European Union Directive. Still, it only refers to the provisions of the Environmental Protection Law and the definitions contained therein (omitting light emissions). Moreover, the EU Directive and the Polish Act cover a closed catalogue of large-scale investments. These circumstances make the regulations related to environmental protection and the provision of information on the environment an ineffective tool for counteracting light pollution.

Two legal acts provide real, although limited, legal grounds for reducing light pollution within the framework of applicable law. The first is the aforementioned Act on Spatial Planning and Development. It gives communes a tool to protect the cultural and natural landscape through a so-called landscape resolution. Through the document, the commune council specifies the rules for placing advertising media. Some of them are illuminated or backlit in a way that generates light pollution. Although the resolution does not contain provisions directly relating to light pollution, the consequence of its adoption may be a reduction in the number of light-emitting sources or a decrease in the intensity of this light.

The second option is to apply the provisions of the Regulation of the Minister of Infrastructure on the technical conditions to be met by buildings and their location (Dz.U., 2022, item 1225). It contains a provision regulating the maximum permissible lighting intensity, among others, on the façades of buildings (including residential buildings). The provision states that lighting devices, including advertisements, placed outside the building or in its surroundings may not cause a nuisance to its users, passers-by, or drivers. Suppose the light is directed towards a building façade containing windows. In that case, the lighting intensity on that façade must not exceed 5 lux for white light and 3 lux for coloured light or light with varying intensity, flashing, or pulsating (par. 293, point 6).

It is also worth mentioning that many new investments in Poland are currently trying to obtain the building research establishment environmental assessment method (BREEAM) certificate [73]. This method of building certification indicates the extent to which the assessed facility is friendly to the natural environment and, on the other hand, how much comfort it creates for its users. This certificate takes into account light pollution as one of the factors influencing the sustainable development of buildings. The BREEAM rating system assesses how a building's design affects the natural environment, including light pollution. Unfortunately, this only applies to the lighting of buildings and their surroundings, not addressing the street lighting problem.

1.4.3. Street lighting as a significant source of light pollution

Road lighting is by far the most widespread and essential in the context of light pollution. This lighting covers practically every road and street, so its impact is tremendous, especially in cities with extensive infrastructure. Of course, light advertising and decorative lighting are also sources of light pollution. Still, they are more local and often concentrated in specific parts of the city (e.g. shopping centres and tourist streets), so their impact on light pollution is minor on a city-wide scale.

As mentioned earlier, the lighting standards in Poland concern the level and uniformity of luminance at the street level. In this aspect, an essential element in the process of designing both indoor [74] and outdoor [75,76] lighting is the "maintenance factor", which takes into account the reduction in the "efficiency" of the lighting system over time, mainly due to the dirtiness of lighting fixtures and the ageing of light sources. In the initial phase of use (operation), road lighting will have a higher "intensity" (will emit a greater luminous flux) than required by standards to compensate for the loss of "power" over time. It is determined at the stage of designing the lighting installation to ensure that the lighting parameters meet the minimum standard requirements throughout the entire period of operation. As a standard, the maintenance factor assumes values below 1.0. This means the designed installations initially provide a surplus of lighting parameters (oversizing). Thanks to this, in the later period of operation (e.g. after a few years), the actual lighting parameters will still meet the minimum standard requirements. In the case of LEDs, the maintenance factor may be higher (closer to 1.0) due to, for example, the possibility of adjusting the luminous flux during use (dynamic control). On the other hand, for traditional luminaires with discharge lamps (e.g. sodium HPS), lower values are assumed, which in practice leads to significant oversizing of the initial road lighting.

Road lighting in Poland is designed following applicable standards (e.g. PN-EN 13201), which specify the minimum required luminance or illuminance parameters (depending on the road lighting category). During the technical acceptance of lighting installations, the correctness of lighting is checked from this angle, considering the road's specificity and surroundings. However, even well-designed installations emit light, which, through reflection from the surface (and other objects), reaches the atmosphere, generating secondary light pollution. Light reflected from the illuminated surface is a significant source of pollution, often underestimated in the design process. This is most noticeable in winter when the reflective properties of the surface change significantly. Failure to consider the ULOR (upward light output ratio) parameter, especially in older installations, causes the direct escape of light into the upper hemisphere. It should be noted that regular, detailed measurements of road lighting parameters during operation are not standard practice in Poland. Moreover, street lighting design still sometimes uses luminaires whose sole purpose is attractive appearance, not considering even the mentioned ULOR parameter and directing most of the light into the upper hemisphere (Fig. 3).

Fig. 3. Lighting of Babina Str. in Kalisz (Poland) implemented using spherical luminaires with a high ULOR coefficient [Photo: Author, 14.07.2023].

1.4.4. Impact of street lighting on the natural environment

The significant impact of light pollution, the source of which is street lighting, on the natural environment has long been noticed. This applies to insects [36−40] or migratory birds [77,78]. Attention was drawn to the increasingly common use of LED luminaires, replacing earlier ones, most often high-pressure sodium (HPS) lamps. In most cases, LED luminaires ensure proper ground lighting, providing the ULOR parameter close to zero. These luminaires usually have a high CCT value, which means a significant share of the blue part in the lamp's spectrum. As has been repeatedly shown, this type of light negatively impacts ecosystems [79−81]. Additionally, it is much more effectively reflected from road surfaces (asphalt, concrete) than in the case of luminaires with a low CCT value, thus becoming a factor that strongly influences the brightness of the night sky glow [82,83].

1.4.4. Switching off street lighting as a method of determining its contribution to the night sky glow

Switching off street lighting in cities, especially during the COVID-19 pandemic, has been used previously to determine the impact of this type of lighting on light pollution [41−46,84]. Of course, such infrastructure elements as illuminated advertisements, large LED screens, decorative lighting and illuminated signs have an impact on increasing the brightness of the light glow. However, these elements constitute a negligible percentage of the light sources escaping into the sky. Moreover, as part of landscape protection, such elements have been removed in many locations, especially in Kraków, as of July 1, 2020.

2. Research area and methods

2.1. Research area

The research was conducted in the Małopolskie Voivodeship in Poland (Fig. 4). The Małopolskie Voivodeship includes 182 communes in 14 urban communes (including the city of Kraków, which is a separate commune), 48 urban-rural communes and 120 rural communes [85]. Information on switching off lighting in Kraków and other locations in the Małopolskie Voivodeship was analysed from among these communes. Based on the monthly averaged VIIRS/DNB images analysis, 22 locations were selected where a significant reduction in radiance was observed in some months of 2020. The study of media reports, as well as information received from local authorities of the surveyed locations, confirmed that in the case of 21 locations in the Małopolskie Voivodeship in 2020, due to the COVID-19 pandemic, municipal lighting was indeed switched off for at least one month. These are Alwernia, Bochnia, Borzęcin, Brzesko, Chrzanów, Dąbrowa Tarnowska, Dębno, Dobczyce, Jabłonka, Kraków, Krynica Zdrój, Krzeszowice, Limanowa, Muszyna, Rabka Zdrój, Skawina, Tarnów, Tymbark, Wadowice, Wieliczka and Zabierzów (Fig. 4).

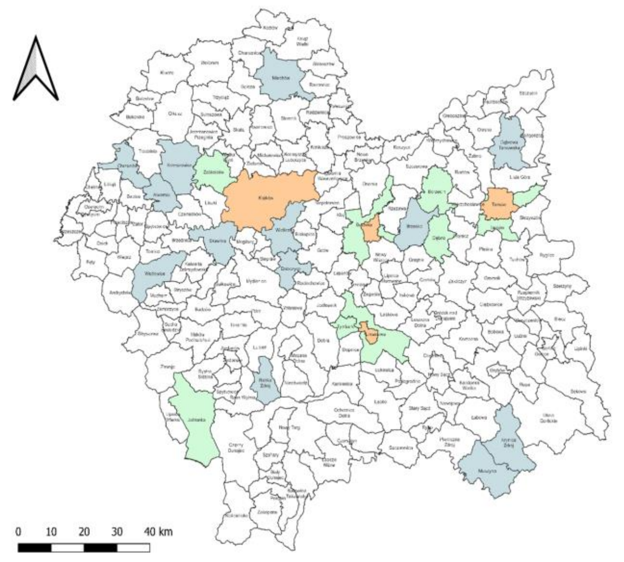

Fig. 4. Małopolskie Voivodeship divided into communes. The communes where street lighting was turned off in 2020 are marked (orange: urban communes; green: urban-rural communes; grey: rural communes).

Of the selected locations, four are seats of urban communes (Bochnia, Kraków, Limanowa, Tarnów), eight are rural communes (Bochnia, Borzęcin, Dębno, Jabłonka, Limanowa, Tarnów, Tymbark, Zabierzów), the remaining are seats of urban-rural communes with varying degrees of urbanisation (Table 1).

Table 1. Localities in Małopolskie Voivodeship, where municipal lighting was switched off in 2020. UG – Commune Office, UM – City Office, UMiG – City and Commune Office).
The pause means that there is no data on the restoration (or not) of street lighting in a given locality.

Commune	Year 2020		Source of data
	beginning	end	
Alwernia	November	—	UG
Bochnia	May 1	September 1	daily press
Borzęcin	May 1	—	UG
Brzesko	April 30	June 30	UG
Chrzanów	June 25	September	UMiG
Dąbrowa Tarnowska	June 1	December	daily press
Dębno	May 11	—	UG
Dobczyce	May 20	—	UMiG
Jabłonka	May 1	August 31	UG
Kraków	April 15	June 1	UM
Krynica Zdrój	mid April	—	VIIRS/DNB
Krzeszowice	April 23	July	UMiG
Limanowa	May 15	August 31	UM, UG
Muszyna	mid April	July	UMiG
Rabka Zdrój	May 14	June 12	UM
Skawina	May 13	September 14	UMiG
Tarnów	April 18	September 25	UG
Tymbark	June 1	—	UG
Wadowice	June 1	September 14	UM
Wieliczka	May 1	September 1	UMiG
Zabierzów	June 1	December 31	UG

2.2. Sources of light pollution

As shown by the analysis of VIIRS/DNB images taken in March 2020, which light sources are also sources of light pollution depends on the nature of the municipality being studied:

- in urban communes, the most light is emitted into space from city centres (e.g. Bochnia, Limanowa), extra-urban economic centres and warehouses (e.g. Bochnia, Limanowa), railway stations (e.g. the Main Railway Station in Kraków), housing estates and academic campuses (e.g. the AGH University campus in Kraków), or some industrial plants (e.g. the ArcelorMittal steelworks in Kraków or the Grupa Azoty company in Tarnów),
- in urban-rural communes, the most light is emitted into space from city centres (in each case), suburban warehouses of various companies (Alwernia, Skawina, Wieliczka), urban and extra-urban industrial plants (Brzesko, Chrzanów, Skawina, Tarnów), quarries (Krzeszowice), summer resorts (Krynica Zdrój, Muszyna, Rabka Zdrój), communication hubs (Rabka Zdrój), and heat and power plants (Skawina),
- in rural communes, the main emitters of light are, first of all, towns that are the seats of communes, and also, most often located nearby, industrial plants and warehouses (Bochnia, Borzęcin, Jabłonka, Limanowa, Tarnów, Tymbark), communication arteries (Dębno), shopping centres (Limanowa), greenhouse complexes (Zabierzów), airports (Zabierzów).

It should be noted that VIIRS/DNB images are taken at approximately 1:00 a.m. local time when residential lighting is no longer active. This means that the main emitters of light are now industrial lighting, advertising lighting, and traffic lights, both pedestrian, road and rail, as shown in [50].

This work aims to research the radiance from municipal lighting. Often, switching off night lighting only concerned localities that were seats of communes. Moreover, it did not affect various industrial plants, warehouses, greenhouses, etc., located in the commune. Therefore, further analysis was limited only to the study of light emission from the areas of localities that were seats of communes (Table 1).

2.3. Turning off the lights in the analysed municipalities

In April 2020, the authorities of many municipalities of the Małopolska Voivodeship, starting with Kraków (the capital of the voivodeship), decided to completely or partially turn off street lighting at night in their areas due to the reduction in street traffic during the developing COVID-19 pandemic. Lighting was switched off automatically at set times (usually at midnight official time). This process was controlled by clocks placed in lighting control cabinets in different lighting zones.

The most widespread action was to switch off city lighting in Kraków [50]. On April 8th, lighting in parks was completely switched off. From midnight on April 15th, street lighting within the city limits, subordinate to the Kraków City Roads Authority, was completely switched off. Street lighting was switched off at midnight and switched on again at 4:00 CEST. From April 22nd, park lighting was synchronised with street lighting. From May 19th, the switching off of street lighting in Kraków was postponed to 1:00 CEST, and this state was maintained until dawn. The only active sources of artificial lighting were fixtures located on private properties, fixtures subordinate to housing communities, some advertising lighting and the lighting of the key junctions (Fig. 2). From midnight on June 1st, standard lighting was restored in the city.

2.4. Analysed communes

The radiance from all municipalities of the Małopolska Voivodeship was analysed. In some cases (Fig. 4, marked in colours), street lighting was turned off at night, most often between midnight and 4:00 CEST. Street lighting is controlled by astronomical clocks placed in each lighting control cabinet in a given area, switching off the lighting in the city successively within a few minutes. Some clocks (e.g. in the Wieliczka commune) were not changed from the so-called winter time (i.e. Central European Standard Time, CET) to Central European Summer Time (CEST), as a result of which the lighting was turned off at 1:00 CEST in the areas served by them. For all the towns that are the seats of these municipalities, a radiance analysis was done based on VIIRS/DNB images.

2.5. Used units

Radiometry is a branch of physics and metrology that deals with quantitative measurements of optical radiation, i.e. electromagnetic radiation in the frequency range of $3 \cdot 10^{11}$ and $3 \cdot 10^{16}$ Hz. The only real difference between radiometry and photometry is that radiometry covers the entire spectrum of optical radiation. In contrast, photometry is limited to the visible spectrum in terms of its influence on visual impressions in the human eye (taking into account the eye's spectral sensitivity) [86]. From the VIIRS/DNB satellite data, the radiance value is obtained, i.e. the radiant flux per unit area per unit solid angle. The symbol of radiance is *L*, while the standard SI unit is W/(m^2·sr) [56]. This publication gives radiance values in derived units nW/(cm^2·sr), in which the VIIRS/DNB data are provided.

2.6. Satellite remote sensing

Images obtained from the Suomi NPP satellite were used to determine the total radiance from the study areas [30]. The photos taken in the DNB (Day Night Band) spectral range [32] are helpful for this work. The centre of this band is at 700 μm; it is 400 μm wide with an imaging resolution of 0.8 km. Raw DNB data require careful processing and consideration of many factors, such as clouds or the angle of the image. Therefore, previously processed data were used in the analysis. In the monthly mean radiance values analysis, ready-made Monthly Cloud-free DNB Composites were used [32,87].

To perform a comparative analysis of the radiance values for specific nights before and after the start date of the lights outage in a given location, daily VIIRS/DNB images downloaded from the Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center at Goddard Space Flight Center (LAADS DAAC) [88,89] were also analysed. During the research period (April – June 2020), VIIRS/DNB images of the study area were taken around 0:10 UTC, i.e. 2:10 CEST. Because the clocks turning off street lighting at midnight in Poland at that time were operating according to CEST, VIIRS/DNB images were taken at a time when the lighting was turned off. It should be noted that for the latitudes of the Małopolskie Voivodeship, there is no daily data from June 2020 from the period near the summer solstice.

2.7. Information about street lighting shutdowns

The local government offices that took these actions provided information on the spatial and temporal scope of street lighting shutdowns in 2020. In addition, information from the local press and residents of the analysed communes was also used.

3. Results and discussion

3.1. Measurement results

Average monthly radiance values obtained from VIIRS/DNB data were used. The radiance value in March 2020 was selected as typical for the period just before the announcement of restrictions related to the COVID-19 pandemic (data from January and February were omitted due to highly variable weather conditions and variable snow cover in those months).

To select the communes where the action of switching off municipal lighting was taken, the VIIRS/DNB image of the Małopolskie Voivodeship from March 2020 was compared with similar images in the following months of 2020. Figure 5 presents VIIRS images for the entire Małopolskie Voivodeship in March and May 2020.

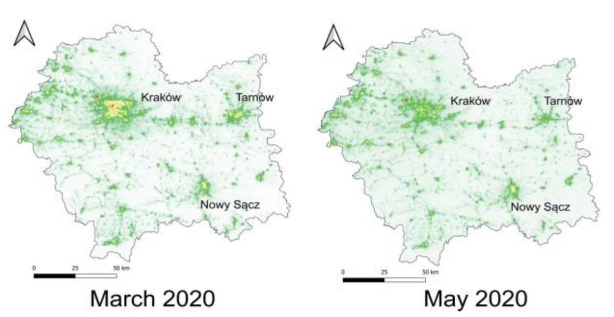

Fig. 5. Radiance from the area of the Małopolskie Voivodeship in March and May, 2020. Visible are the largest cities of the region: Kraków, Tarnów and Nowy Sącz. (EPSG:2180 - ETRF2000-PL coordinate system).

Based on this analysis, 21 communes were initially selected where a significant reduction in radiance was observed in various months of 2020 compared to March of this year. A question was sent to the authorities of all communes selected in this way, asking whether these shutdowns had taken place, and if so, they were asked to provide details of this action. Positive responses, including the dates and times of switching municipal lighting on and off, as well as the territorial scope of the action, were received from 12 communes; in the remaining cases, this data was recreated based on information from the local press or from communal orders publicly available on the Internet. No confirmation could be obtained from only two communes, Krynica Zdrój and Muszyna – they were included in the analysis because the reduction in radiance on VIIRS/DNB images in these cases is apparent and cannot raise doubts.

Radiance changes in some selected communes in Małopolskie Voivodeship have already been analysed in other publications [50,51]. As part of these studies, it was found that the results of these analyses were often influenced by light sources associated with industrial plants, warehouses, shopping centres, greenhouses, etc., located within the commune, most often outside the areas of dense construction. These sources, which contribute significantly to the total radiance from the location of a given commune and are not subject to local authorities, were not excluded as part of the described actions to reduce municipal lighting. This means that the quantitative conclusions drawn from our analyses may sometimes not be entirely correct. To avoid this effect, this analysis was limited to measuring radiance only from the area of localities that are the seats of municipal authorities.

In some cases, when there are strong light sources within the boundaries of the locality which are not municipal lighting (e.g. industrial plants, greenhouses, etc.), it was limited to areas where these sources do not occur (e.g. Tarnów). Table 2 presents the average monthly radiance values obtained from analysing VIIRS/DNB images for 21 selected localities in the Małopolskie Voivodeship in March (pre-pandemic radiance) in the month when the most significant number of municipal lighting was turned off (minimum pandemic radiance) (Fig. 6). The population of these localities, the area covered by the analysis, and the absolute and relative change in radiance in this area are also given.

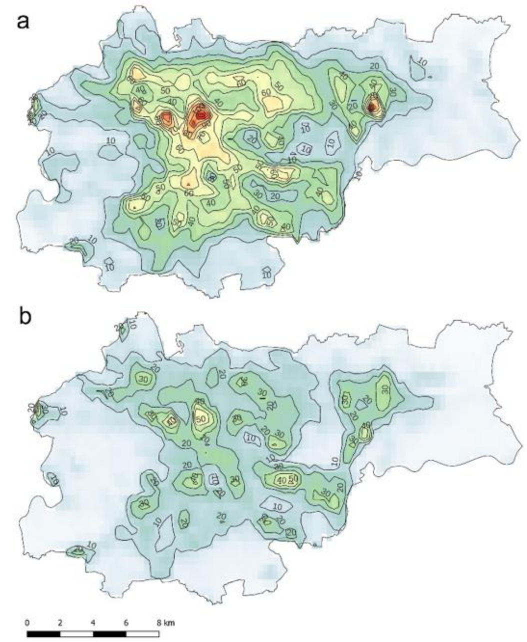

Fig. 6. Example radiance changes resulting from switching off municipal lighting in 2020 for Kraków: (a) March 2020, (b) May 2020. Contour labels are expressed in nW/(cm^2·sr).

3.2. Discussion

3.2.1. Analysis of radiance measurements

As can be seen, of the analysed locations, the city of Kraków emits the most light into space (over 26 000 nW/(cm^2·sr)), while the village of Borzęcin emits the least light (only 33 nW/(cm^2·sr)).

Figure 7 shows the dependence of radiance on population. A clear linear dependence (with the correlation coefficient R=0.9403) was found between the logarithms of these quantities. This dependence is consistent with the proposed models [13,15].

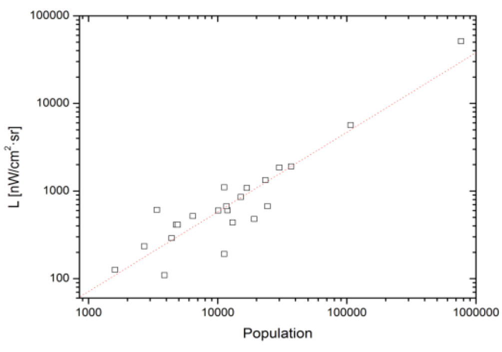

Fig.7. Radiance from selected localities of the Małopolskie Voivodeship as a function of the population size of these localities (R=0.9209; p-value < 0.01).

The pie chart (Fig. 8) shows the distribution of localities in the Małopolskie Voivodeship depending on the size of the reduction in relative radiance resulting from switching off municipal lighting. The communes in which the lockdown caused the greatest reduction in radiance (60-80%) were by far the most numerous.

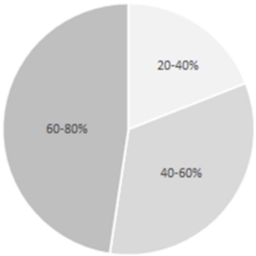

Fig. 8. Distribution of the number of localities in the Małopolskie Voivodeship depending on the size of the reduction in relative radiance as a result of switching off municipal lighting.

A statistical cluster analysis was performed to obtain a more complete picture of the impact of municipal lighting shutdowns on the radiance of individual locations. Three clusters of locations can be distinguished based on the elbow analysis and the analysis of the obtained dendrogram (Fig. 9). Due to the size of the relative reduction in radiance, these clusters concentrate around the average value of (67 ± 5)% (cluster I), (48 ± 3)% (cluster II) and (36 ± 4)% (cluster III). The group represented by cluster I includes locations where all street lighting was switched off. Cluster II contains locations where part of the street lighting was left on, which is considered essential for the proper functioning of the city. In the case of Kraków, the fact that advertising lighting, some parking spaces, etc., were left on is undoubtedly significant here. In the locations covered by cluster III, only the illumination of peripheral, less essential streets was switched off. In the case of Wadowice, the lighting of the two main through streets, the City Park and the city's central square (Plac Jana Pawła II) was left. As can be seen, these facilities significantly contribute to this town's total radiance.

The above analyses show that the contribution of all municipal lighting to the total radiance of a given locality is approximately 67%. Comparing the dendrogram data with Table 2, it was found that in the case of cluster I, the most significant reduction in radiance, amounting to even 80%, occurred for small towns (Dębno), where the dominant source of night lighting is street lighting. In comparison, the remaining 20% can be related to the illumination of private properties. Large cities in this cluster (Bochnia, Tarnów, Chrzanów, Wieliczka) recorded a reduction in radiance by approx. 67%. The remaining 33% is probably due to the lighting of housing cooperatives (not subject to municipal authorities), single-family private houses, workplaces, advertising banners, etc. This effect is even more visible for Kraków, the capital of the Małopolskie Voivodeship, which, together with Skawina, with a reduction in radiance by almost 50%, was included in cluster II.

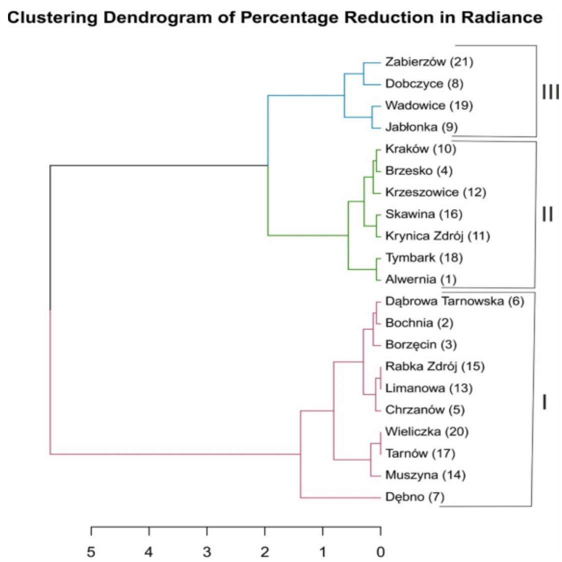

Fig. 9. Dendrogram showing the grouping of the analysed localities in terms of the percentage reduction in radiance during the street lighting shutdown period.

Table 2. Summary of radiance measurements in selected communes of the Małopolskie Voivodeship in March 2020. Krynica Zdrój and Muszyna, for which no confirmation of switching off municipal lighting was received, are marked in italics.

No.	Locality	Area, km²	Population	Pre-pandemic radiance, nW/(cm²·sr)	Minimal pandemic radiance, nW/(cm²·sr)	Absolute change in radiance, nW/(cm²·sr)/km²	Relative change in radiance, %
1	Alwernia	19.64	3380	609	217	265	44
2	Bochnia	20.55	29992	1856	584	1273	69
3	Borzęcin	3.37	3865	109	33	76	70
4	Brzesko	9.92	16827	1085	559	526	48
5	Chrzanów	20.61	37123	1913	656	1257	66
6	Dąbrowa Tarnowska	8.35	11924	602	195	406	68
7	Dębno	2.80	1601	126	25	100	80
8	Dobczyce	12.45	6425	518	360	158	31
9	Jabłonka	18.74	4767	412	247	164	40
10	Kraków	520.98	766683	51472	26311	25161	49
11	*Krynica Zdrój*	*28.00*	*11243*	*1101*	*539*	563	51
12	Krzeszowice	7.88	10090	600	317	283	47
13	Limanowa	10.62	15132	855	280	575	67
14	*Muszyna*	*8.08*	*4909*	*412*	*161*	251	61
15	Rabka Zdrój	6.75	13052	438	143	295	67
16	Skawina	5.43	24325	669	332	337	50
17	Tarnów	32.55	107045	5647	2098	3549	63
18	Tymbark	5.04	2700	235	123	112	45
19	Wadowice	2.92	19149	479	297	181	38
20	Wieliczka	8.90	23395	1334	494	840	63
21	Zabierzów	3.93	4400	291	190	100	35

To identify the factor determining the reduction in radiance, principal component analysis (PCA) was performed (Fig. 10).

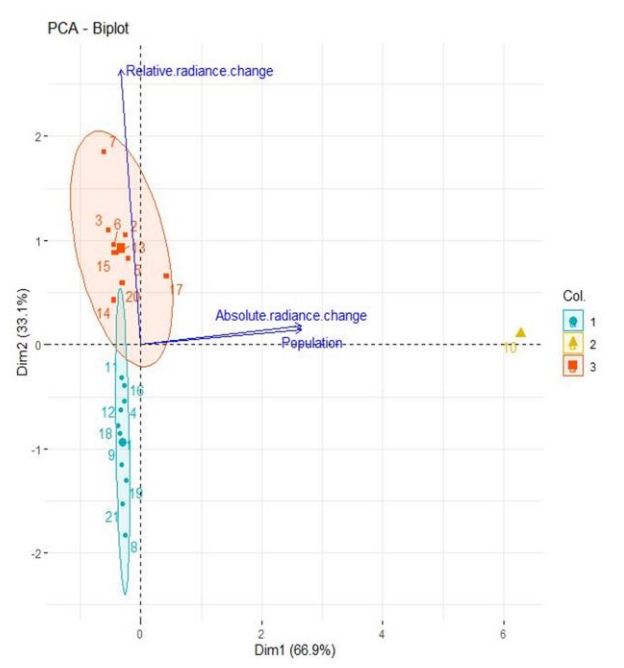

Fig. 10. PCA analysis showing the influence of principal components on the grouping of the analysed locations.

This analysis shows that the dominant factor influencing the variance for Kraków (point 10) is the absolute radiance change and population. The remaining locations are divided into two clear groups, in which the variance is caused by the relative radiance change: 1 (Alwernia, Brzesko, Dobczyce, Jabłonka, Krynica Zdrój, Krzeszowice, Skawina, Tymbark, Wadowice, Zabierzów) and 2 (Bochnia, Borzęcin, Chrzanów, Dąbrowa Tarnowska, Dębno, Limanowa, Muszyna, Rabka Zdrój, Tarnów, Wieliczka). I believe that the share of municipal lighting in the total radiance of the location is responsible for this division.

3.2.2. Energy losses related to municipal lighting

Energy losses due to lighting the night sky should be understood as the part of electricity related to municipal lighting, which is directed directly into space and through reflection from the ground. In the latter case, it should be noted that the reflection of light from the ground does not always mean a loss of energy in the physical sense. Energy losses in lighting result mainly from emission of light in undesirable directions (e.g. upwards) and not necessarily from the reflection itself. If light were not reflected from the illuminated surface, it would not be visible to people. One should only strive for the luminance of such illuminated surfaces to be optimal, not causing a burden to the sense of sight, while ensuring the safety of users of the space.

In 1999, based on data from DMSP satellites, daily energy losses for city lighting were determined for all major cities in Japan and for several cities worldwide. Among them, Polish cities included Warsaw (with the result of $8.81 \cdot 10^6$ kWh) and Kraków (with the result of $4.40 \cdot 10^6$ kWh) [60]. It is difficult to relate these numbers to the current situation; one can only estimate how much electricity is currently lost for lighting the sky.

In 2018–2019, the average annual electricity consumption in Kraków, excluding households, amounted to $2.74 \cdot 10^6$ MWh [90], which gives $7.50 \cdot 10^6$ kWh per day. Street lighting costs constitute 38% of the total electricity consumption costs in the city [91], costing 29.5 million PLN per year. According to an analysis conducted by the International Dark Sky Association, approx. 35% of electricity is wasted on lighting the sky [91]. In the case of Kraków, this gives energy losses of around 10 million PLN (approx. 2.3 million EUR) per year. At the same time, on this basis, it is possible to determine the amount of Kraków's daily energy losses on lighting the sky at approx. $2.85 \cdot 10^6$ kWh. This significantly lower value than that given for 1999 is probably related to the systematic replacement of energy-intensive HPS lighting with energy-saving LED lighting. In 2017, approximately 3 000 sodium HPS fixtures were replaced with LED fixtures [92]. Currently, HPS fixtures constitute approximately 36% of all street fixtures in Kraków [93].

4. Conclusions

Satellite data analysis has shown that turning off municipal lighting significantly reduces radiance. When this type of lighting was turned off, in locations where it is the dominant source of artificial light at night, the radiance decreased by almost 70% (sometimes even 80%) compared to the pre-pandemic value. In large cities, where there are other light sources, such as industrial plants or advertisements, the radiance decreased by almost 50% in addition to street lighting. Turning off only the lighting of some peripheral streets reduced the radiance by only about 36%. A reduction in radiance by about 50% was also noted in smaller towns, where the lighting of the main streets was left on. It can be concluded from this that reducing the lighting of even just residential or local streets significantly reduces the emission of artificial light into the sky. Of course, it is not possible to permanently turn off this type of lighting. Still, it is possible to consider permanently leaving the lighting on only the main streets while installing motion sensors on low traffic, e.g. residential or local streets. The presented analysis shows that reducing light emissions into the sky by several dozen per cent is possible, which brings significant energy savings. A systematic replacement of street lighting fixtures in Kraków with energy-saving LED lighting is being carried out. Annual monitoring of radiance values from the Kraków area is planned to verify the thesis about the decrease in radiance.

Of course, the most beneficial solution would be implementing more advanced street lighting management systems, such as intelligent lighting control depending on vehicle traffic intensity. A similar system was analysed by the author of this paper in 2018 in Zselic Starpark (Hungary). Inside the park are localities where street lighting emits light of minimal intensity in the idle state, allowing only to distinguish objects on the ground. When a pedestrian or a car moves, the luminaires brighten only in the wake of the moving object. As a result, the lighting of the locality has a minimal impact on both local ecosystems and astronomical observations conducted within the Zselic Observatory [94].

Of course, it should be remembered that the basic task of street lighting at night is to ensure the safety of street users. However, it is necessary to implement solutions consistent with the principle of sustainable development – street lighting should provide life comfort for its users while minimising the impact on the natural environment. This is possible thanks to adopting standards that consider light pollution. It is often argued that such standards will cause living in the dark. Replacing lighting fixtures usually leads to better ground illumination while limiting light emission into the environment [95]. In 2013, a survey was conducted in Finland on a sample of 2053 people, aiming to present the harmful aspects of lighting and how the public perceives pollution [96]. The results show that residential and street lighting are considered the most common sources of light pollution, while commercial lighting is the most irritating form of light use. Respondents universally regarded light pollution as an interference with outdoor recreation and relaxation. The survey results indicate that light pollution's ecological and health effects are generally weakly reported, while aesthetic effects are emphasised.

In Poland, in 2020, a study was conducted on the impact of changing the illuminance of streets and sidewalks in the Żywieckie Housing Estate in Kraków after replacing HPS luminaires with LED lighting [97]. During the study, several randomly encountered residents, most often walking their dogs, were asked about their opinion on the impact of these lighting changes on the quality of their lives. The interviews showed that the new luminaires illuminate the ground better while limiting the penetration of light into the interior of the apartments. The surveyed residents noted an improvement in the visibility of the ground, which is essential, for example, during evening walks with the dog. On the other hand, they stated that the housing estate had become "darker". In general, the opinion of residents was that the lighting should be such as to ensure safety during evening and night walks. Of course, such statements do not constitute the basis for any statistical analysis; they are only signals from a selected group of sidewalk users. This type of analysis requires broader studies covering all areas where this type of lighting replacement occurred. Such studies are planned.

It is also important to note the apparent conflict between lighting professionals, with a background in lighting design, who often criticize calling light "pollution," and light pollution experts, with a background primarily in astronomy and the environment. In 2019, a survey was completed by 205 participants, identified as "lighting professionals" and "light pollution experts" [98]. Analysis of the survey revealed that, despite their seemingly conflicting interests, lighting professionals and light pollution experts largely agree on the definition of the problem and approaches to solving it.

This paper aims to show the current status of the described problem in Poland, where no standards or laws regarding protection against light pollution have been introduced yet. This is important when the Light Pollution Think Tank is trying to introduce such legal provisions [68].

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