FULL GUIDE

MONITORING LIGHT POLLUTION

Guidance for measuring light pollution, assessing its impact on biodiversity, and planning artificial light at night

Interreg North Sea

Co-funded by the European Union

DARKER SKY

Interreg
North Sea

Co-funded by
the European Union

DARKER SKY

MONITORING LIGHT POLLUTION

Guidance for measuring light pollution, assessing its impact on biodiversity, and planning artificial light at night

Published by DARKER SKY Interreg North Sea Project
August 2026

Authors in alphabetical order:

Dr. Andreas Hänel
Working Group Dark Sky der Vereinigung der Sternfreude e.V.

Prof. Dr.-Ing. Carolin Liedtke
HAW Hamburg University of Applied Science

Athleen Selma Rietze
Carl von Ossietzky Universität Oldenburg

Yoann Roulet
Université de Bretagne Occidentale

Jan-Willem van Kruyssen
Landmakers Cooperatie U.A.

DARKER SKY is carried out in the framework of the Interreg North Sea Programme under the Programme Priority 3 "Sustainable North Sea Region" and the Specific Objective 3.2 "Develop new methods for the long-term sustainable management of North Sea ecosystems". The programme is funded by the European Regional Development Fund (ERDF) of the European Union.

CONTENTS

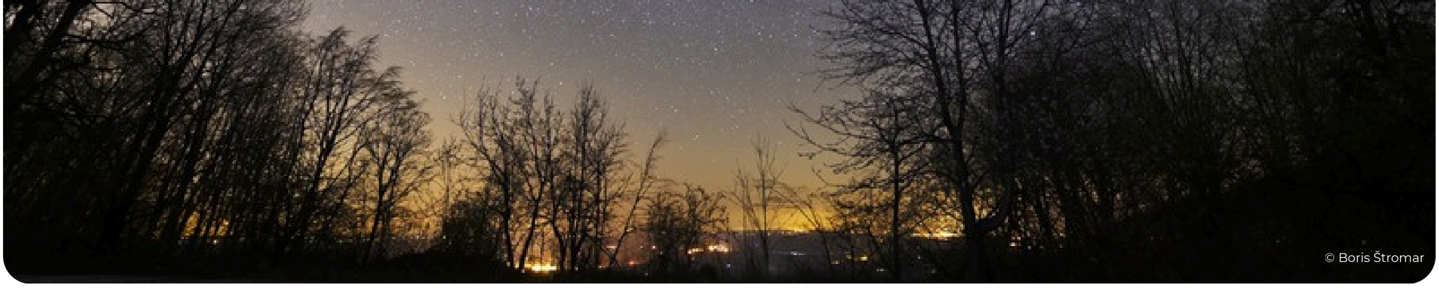
© DARKER SKY

1 DARKER SKY AND LIGHT POLLUTION

About the DARKER SKY Project

DARKER SKY is an Interreg North Sea project which aims at reducing light pollution and **increasing biodiversity and ecological connectivity** in the North Sea Region (France, Germany, the Netherlands & Denmark) by providing municipalities and ports with innovative **measuring, monitoring and co-design methods** for the implementation of environmentally sound and energy-efficient **light reduction solutions** benefitting biodiversity and communities.

By doing so, the project supports the EU Zero Pollution Action Plan and the EU Nature Restoration Law, helping to create dark ecological corridors and reduce habitat fragmentation.



© Boris Štromar

Understanding light pollution

Light pollution is (excessive or misdirected) **artificial light** that brightens the night sky and local ecosystems, **disrupting natural patterns**. In the North Sea region, it is mainly caused by urban, peri-urban and rural areas, ports and industrial activities. Coastal areas experience significant light pollution due to their proximity to human settlements and maritime activities. Over the past decades, light pollution has steadily increased due to urbanization, economic activities, decreasing cost of brighter LED lamps and the extensive use for public and work safety and operations.

Ecological impact

Light pollution has a profound effect on biodiversity. It disrupts natural light cycles and affects wildlife from genetic to landscape scale. For example, it can:

- alter gene expression, decrease foraging time and body mass, and thereby **reduce survival capacity**
- alter seasonal activity patterns (e.g. budburst or migration) which may cause organisms to **respond too early or too late** to favourable environmental conditions
- attract and trap animals, **increase predation and parasitism risk** and alter population balance

MONITORING FRAMEWORK

This overview provides municipalities, ports and other stakeholders with general guidelines to map and monitor light pollution and its environmental impact.
These guidelines are intended to improve municipal capacity to fulfil current and upcoming national requirements for identifying, planning and implementing environmentally sound lighting infrastructure.

The guide focuses on two main areas:

- **measuring light pollution**
- **assessing its impact on biodiversity**

The monitoring framework includes two key protocols:
one for measuring and monitoring **light levels** and another for investigating ecological **effects on biodiversity** through selected sensitive groups such as birds, bats, insects and marine life.

Monitoring was carried out before and after lighting modifications at the DARKER SKY pilot sites in order to assess their impact on light pollution and biodiversity. Sociological surveys complemented these protocols by assessing how local communities perceive light pollution and the new lighting modifications.

Pre-measurement		Post-measurement
Light measurements	Light modifications	Light measurements
Biodiversity measurements		Biodiversity measurements
Sociological survey		Sociological survey

Societal dimension and co-design process

Artificial light at night is a technical and ecological issue, but also has a **societal dimension.** Public lighting influences perceptions of **safety, comfort and spatial identity.** For this reason, light-reduction strategies require not only technical optimisation, but also **stakeholder involvement and social understanding**.

Within DARKER SKY, several demonstrator sites have integrated structured **co-design processes** into technical planning. These include participatory workshops, night walks, surveys and interactive scenario testing. In selected pilot regions, immersive tools such as 3D modelling and Virtual Reality have been used to visualise alternative lighting scenarios. Stakeholders can simulate adjustments in colour temperature, dimming levels and shielding, which supports informed dialogue between technical experts and local users.

Experience from the pilot regions indicates that these approaches can also **support behavioural adaptation**. In some cases, residents and businesses voluntarily adjusted private lighting installations, reduced illumination levels or installed timers and motion sensors. These decentralised measures **extend the overall light-reduction effect beyond the modified public luminaires.**

The societal dimension is therefore an important component of sustainable light management. Technical measurements quantify lighting parameters and ecological monitoring assesses biodiversity effects, but **long-term effectiveness also depends on awareness, acceptance and responsible use**. Integrating participatory methods and experiential tools can strengthen the durability and transferability of light-reduction strategies.

2 ECOLOGICAL EFFECTS MONITORING

>> Biological indicators are essential for assessing the effectiveness of night quality restoration efforts. In fact, the effects of light adaption on ecosystem, like intensity reduction and color modification, are still poorly known (Roulet et al., 2026).

Those indicators should be selected based on:

- ecological, regulatory and cultural relevance
- monitoring cost and required expertise
- broad distribution across Europe
- relatively well-known and rapid behavioural responses to artificial light at night

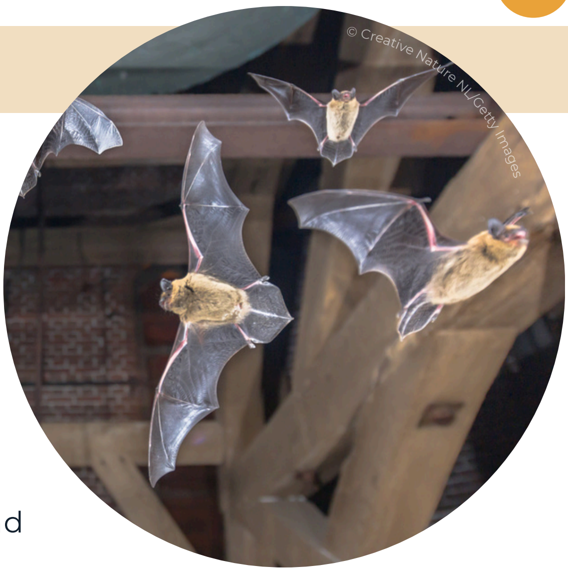
Within DARKER SKY, a **standardized project protocol** was developed to monitor the effects of artificial light at night on selected diurnal and nocturnal taxonomic groups and species. The protocol focuses on **light pollution impact on corridors used by fauna** for migration or commuting between habitats, as well as on local marine and terrestrial habitats that support biodiversity.
Each partner region conducted monitoring whether changes at the pilot sites affected local and migratory species in terrestrial and marine environments.

A **summarised overview** can be found in *Table 1*. In the following, monitoring recommendations will be documented per species groups and DARKER SKY examples will be given.

SUMMARY	HOW?	WHAT?	WHEN?
BATS	Acoustic monitoring with automated ultrasonic recording	• Acoustic activity and temporal distribution • identifying species (groups) and behaviour	Late spring to early autumn
BIRDS	• Automated acoustic recording • Point/transect counts • Camera traps	• Acoustic activity and temporal distribution • Species diversity and abundance • Phenology	• late winter to early summer • season-round monitoring
INSECTS	Capture-based sampling (e.g. sticky traps)	Abundance and diversity of ALAN sensitive insect species groups	Late spring to early autumn
BENTHIC FAUNA	Plot-based sampling (e.g. quadrats)	Biomass, diversity and community composition	Spring and autumn

Table 1. Summary of the ecological effects monitoring methods

BATS



- Bats are the second most diverse mammal group in Europe, with more than 40 species.
- Species differ strongly in habitat use, behaviour and migration patterns.
- Some species are associated with natural landscapes (e.g. Myotis bechsteinii), while others are common in urban areas (e.g. Pipistrellus pipistrellus).
- All bat species are disturbed by light pollution and generally avoid illuminated areas.
- Species with long-range echolocation calls (Pipistrellus, Eptesicus, Nyctalus) are often more light-tolerant.
- Species with short-range echolocation calls (Myotis, Rhinolophus) are particularly sensitive to artificial light.

WHY?

Bat activity is a useful indicator of light-pollution effects at local to landscape scale. Monitoring migratory species during spring and autumn can provide information on impacts on **migratory behaviour and the hosting capacity of ecological corridors**. Acoustic monitoring offers a cost-efficient, non-intrusive approach, as echolocation calls are linked to morphology, ecology and behaviour. These calls can be used to identify **species or species groups**, while differences between hunting and commuting calls also allow **behavioural assessment.**

WHEN?

	BATS
SEASON	Late spring to early autumn when foraging and echolocation activity are highest
MIGRATION	Spring and autumn
TIME OF NIGHT	Throughout the night ideally from one hour before until one hour after nightfall.
WEATHER CONDITIONS	No rain, little wind and preferably no cold or full-moon nights.
WINTER MONITORING	Generally not recommended in temperate regions because bats are hibernating and acoustic activity is low.

HOW?

Equipment

- Bat detector (AudioMoth, Batlogger, Pettersson, Wildlife Acoustics)
- Sufficient storage capacity
- *Optional*: smartphone detector for casual observations or public outreach

Field deployment

- Place detector at monitoring site
- Record throughout the night
- Repeat measurements over multiple nights

Data analysis

- Automatic identification software (e.g. Tadarida, SonoChiro)
- Expert validation recommended
- Compare activity between lighting conditions or over time

BIRDS

- Europe hosts more than 530 bird species, predominantly passerines.
- Millions of migratory birds move along the North Sea and Atlantic coasts, especially at night.
- Annual and daily bird activities are strongly influenced by light.
- Artificial light at night can attract or disorient nocturnally migrating birds and increase collision risks.
- It can disrupt circadian rhythms, alter sleep patterns and advance dawn chorus.
- Artificial light may also affect foraging and reproduction by shifting the timing of feeding and breeding behaviour.

WHY?

Birds are highly **responsive** to changes in natural and artificial light throughout their annual cycle. Monitoring can help assess impacts on **breeding activity, migration behaviour, habitat use and ecological connectivity**. Because bird vocalisations can be recorded and analysed automatically, acoustic monitoring provides a practical, non-intrusive approach for evaluating ecological effects of lighting changes over time.

WHEN?

	BIRDS
BREEDING SEASON	Late winter–early summer Assess population size, reproductive success and habitat use during the breeding season.
MIGRATION	Spring and autumn Assess migration timing and ecological connectivity.
WINTER MONITORING	Assess habitat use and overwintering populations
YEAR-ROUND (*WHERE POSSIBLE*)	Capture daily and seasonal variation.
DARKER SKY EXAMPLE	March to the end of May, when migratory activity is high and the reproductive period begins.

© DARKER SKY

HOW?

Equipment

- Automated acoustic recorders
- *Optional*: camera traps or video monitoring
- For larger-scale monitoring: radar, thermal imaging, GPS or radio telemetry

Field deployment

- Conduct point counts or transect walks to record birds seen or heard during defined periods.
- Monitor reproductive activity through breeding pairs, offspring numbers or offspring survival.
- In urban areas, record nest-box phenology, including occupancy, nest building, egg laying, feeding and fledging.
- Record singing and calling activity continuously where acoustic monitoring is used.

Data analysis

- Analyse recordings with automated identification software such as BirdNET.
- Citizen science platforms such as eBird can provide complementary large-scale data.
- AI-based tools can support the processing of recordings and images.
- Expert validation is recommended.

FLYING ARTHROPODS (INSECTS)

- Artificial light at night strongly affects flying arthropods such as moths, beetles and flies.
- Many species are attracted to light, causing disorientation, exhaustion and increased predation risk.
- Other species are repelled by light, reducing activity in illuminated areas.
- These effects can disrupt pollination, food webs and ecosystem balance.
- Flying arthropods are important pollinators, prey and decomposers.
- Artificial lighting often reduces abundance and diversity in brightly lit environments.
- Reduced insect abundance may also affect insectivorous and migratory birds

WHY?

Flying arthropods respond directly to artificial light and can provide information on ecological effects of lighting changes. Monitoring abundance and diversity helps assess impacts on **local biodiversity, ecosystem functioning and food availability for other species.**

WHEN?

	FLYING ARTHROPODS
SEASON	Late spring–early autumn
PEAK PERIOD	Warm summer nights
TIME OF NIGHT	Several hours after sunset
WEATHER	Clear, warm and calm nights
AVOID	Rain, wind and low temperatures
DARKER SKY EXAMPLE	May–July; continuous monitoring for 48 hours each month

HOW?

Equipment

- capture-based sampling, e.g.: sticky traps, malaise traps, light traps, pan traps, sticky traps,
- *Optional*: automated sensors or molecular methods

Field deployment

- Use standardised traps to monitor abundance and diversity.
- Combine trapping with transect counts for conspicuous groups where appropriate.
- Monitor for several hours of darkness or continuously using standardised protocols.
- Long-term and standardised monitoring is recommended for detecting changes over time

Data analysis

- Assess abundance and diversity of flying arthropods.
- Molecular methods and automated sensors can support detailed community analysis.
- Compare results across sites and monitoring periods to detect changes associated with lighting conditions.

BENTHIC FAUNA

- Artificial light at night increasingly affects marine ecosystems.
- Many benthic invertebrates rely on natural day–night cycles to regulate grazing, foraging, reproduction and predation.
- Artificial light can alter community composition, nocturnal activity and predation risk.
- Organisms in the intertidal zone are particularly sensitive to environmental change and serve as good bio-indicators.
- The mechanisms and consequences of light pollution for benthic biodiversity remain insufficiently understood.

WHY?

Benthic communities are sensitive to changes in natural light conditions and can provide information on **ecological effects of artificial light in marine ecosystems**. Monitoring can help assess changes in community composition, abundance and ecosystem functioning, and evaluate whether lighting modifications influence benthic communities.

WHEN?

	BENTHIC FAUNA
SEASON	Spring and autumn reach peak abundance and biomass and community composition
PEAK PERIOD	Warm summer nights
TIME OF DAY/NIGHT	Generally less critical
CONDITIONS	Stable water flow, temperature and oxygen levels
AVOID	Peak emergence periods at night
DARKER SKY EXAMPLE	March–May

HOW?

Equipment

- Quadrat survey frames
- Field identification guides

Field deployment

- Use quadrat surveys to standardise sampling areas.
- Identify benthic fauna and flora in the field.
- Compare densities between sites or conditions.
- Assess the community as a whole.

Data analysis

- Evaluate organism density, cover and size.
- Compare results between conditions.
- Assess community composition and functional behaviour.

3 LIGHT MEASUREMENTS

>> Assessing light pollution involves measuring different parameters, such as:

- how much light hits a surface (illuminance)
- how bright a surface appears (luminance)
- or the light colour.

To collect detailed data on lighting conditions, different measures are included in the monitoring methodology. This is crucial for evaluating the **effectiveness of lighting modifications.**

The photometric units refer to the spectral sensitivity of the human eye under daylight conditions, known as photopic vision. Photometric units such as candela (cd), lumen (lm) and lux (lx) refer to this spectral sensitivity.

A summary of the most important quantities is given in the following chapters.

ILLUMINANCE

IN SHORT

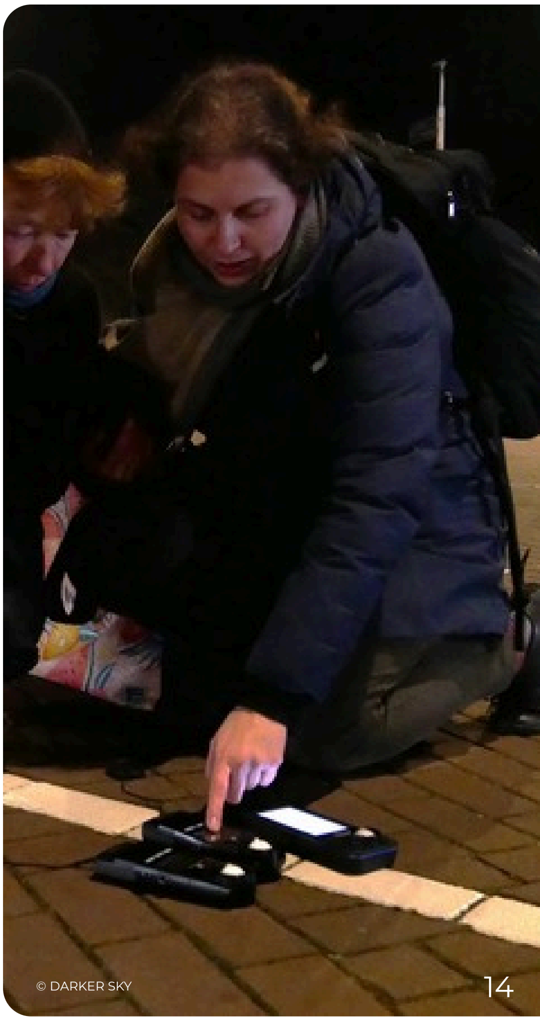
The amount of light falling onto a surface, indicating how brightly an area, such as a street or square, is lit (*Table 2*). It helps assess whether lighting levels provide safety and visibility without being excessive.

Unit: lux (lx)

Method:

- Measured with a lux meter
- typically on a grid to determine mean values
- professional calibrated instruments are recommended for accurate and long-term monitoring

Illuminance is measured with a lux meter placed on the ground or on the surface of interest. To determine the mean illuminance of an area, measurements are taken on a grid. *Figure 1* shows the simplified measuring grid used in the DARKER SKY project, based on EN 13201 (source) and van Bommel (2015).



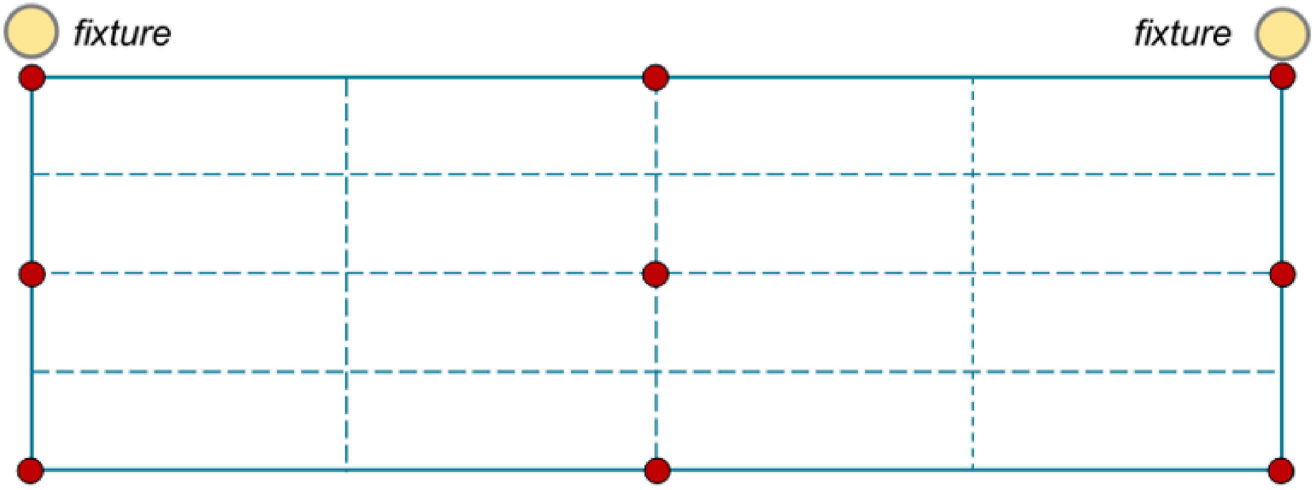


Figure 1: Simplified measurement grid introduced in the DARKER SKY procedures for assessing the mean illuminance of streets or squares. The red dots indicate the measurement points, while the large yellow circles with the label "fixture" represent the luminaires/light sources (Configuration of the simple measuring grid adapted from van Bommel, 2015, by C. Liedtke).

Smartphone apps for measuring illuminance and most low cost lux meters have low accuracies (often 10% and more) and can only be used for a **basic orientation**, especially at luminances below 10 lx.

Professional lux meters, which are calibrated according to international standards (e.g. DIN or ISO), typically cost between 1000-2000 EUR. These instruments achieve a **much higher accuracy,** often within ±3–5% and are suitable for **official assessments or long-term monitoring.**

For municipalities, inexpensive devices can already provide a rough overview of lighting conditions. However, when precise data is required (e.g. for legal or planning purposes), professional calibrated instruments are recommended.

SITUATION/ENVIRONMENT	TYPICAL ILLUMINANCE [lux]
Clear night sky without moon (natural)	~ 0.001
Full moon on clear night	~ 0.2
Urban skyglow (bright city sky)	0.5
Residential street (EN13201 P class)	2 - 15
Main road or busy street (EN13201 C class)	7.5 - 30
Sports field (football)	75 - 2000
Daylight overcast	< 5 000
Daylight sunlight	< 100 000

Table 2: Typical ground-level illuminance (lux) values for common situations, measured using a lux meter (Haenel et al, 2018, European norms, own measurements)

CORRELATED COLOUR TEMPERATURE (CCT)

IN SHORT

CCT indicates the colour appearance of a light source.
Lower colour temperatures produce warmer light with less blue content, while higher colour temperatures produce cooler white light with more blue content and potentially stronger ecological and health impacts.

Unit: Kelvin (K)

Method:
spectrometer or a light meter equipped with a CCT function

Correlated Colour Temperature (abbr. CCT) indicates the colour appearance of a light source, measured in *Kelvin (K)*. It is a first approximation to estimate the **blue spectral content of a white light source**.

Lower values (e.g. 2,700 K) correspond to **warm, yellowish** light, while higher values (e.g. 4,000–6,500 K) correspond to cool **white light** with a higher proportion of blue.
CCT is important to consider in the context because light with higher blue content can have **stronger ecological and health impacts** for humans.

The correlated colour temperature is determined by a **spectrometer** or a light meter equipped with a CCT function. The device analyses the spectrum of the light source and calculates its colour temperature in Kelvin. According to EU standards CCT must be indicated on the light source or its packing. The following chart (*Table 3*) summarizes typical CCTs and their impact on insects.

CCT [K]	LIGHT APPEARANCE	TYPICAL IMPACTS ON INSECTS
< 2,400	Amber, Orange, Gold	Very low attraction on most fauna
< 3,300	Warm white / yellow	Low attraction; fewer insects are drawn
3,300 – 5,300	Neutral white	Moderate attraction; some nocturnal insects affected
> 5,300	Daylight / Cool white	Strong attraction; most insects, especially flying nocturnal species, are highly attracted

Table 3: Typical CCTs (based on EN 12464-, Tab. 6) and their impact on insects

LUMINANCE

IN SHORT

Luminance describes the brightness of a surface emitted or reflected in a specific direction (as perceived by the human eye), evaluating glare, road lighting, building facades, and public displays

Unit: candela per square meter (cd/m²)

Method:
- Luminance meters can be handheld devices for spot measurements or camera-based systems for mapping brightness over larger areas or longer times.
- with additional fixation equipment (e.g. a tripod)


©Piet Zijlstra PolyCiviel


© HAW Hamburg University of Applied Science

Unlike illuminance meters, which measure light falling on a surface, **luminance meters measure the light emitted from a light source or light reflected from a surface in a specific direction**.

Luminance meters can be handheld devices for spot measurements or camera-based systems for mapping brightness over larger areas or longer times.
They are widely used to evaluate **glare, road lighting, building facades, and public displays**. Since the luminance is direction-dependent, luminance meters should be used with additional fixation equipment (e.g. a tripod) to ensure a stable measurement.

When measuring luminance outdoors, natural factors such as weather, humidity, and surface conditions can significantly influence the results. Wet or reflective surfaces, like rain-soaked streets, increase measured luminance, while fog, mist, or heavy clouds bias the measurement very much.
So, they should be performed under **stable, dry conditions** to ensure consistency, and multiple readings may be needed to account for natural variations throughout the night.

The following *Table 4* shows typical luminance values.

SITUATION/ENVIRONMENT	TYPICAL LUMINANCE [cd/m2]
Clear night sky (no moon, natural)	0.0002
Main street or urban road (M class EN13201)	0.3 - 2
Displays	50 - 1000
Signs/Billboards	10-2500
LED flood lights	200 000 – 2 000 000
Surface of the sun	1 600 000 000

Table 4: Typical luminance values obtained under optimal conditions (Haenel et al. 2018, standards, own measurements).

Luminance meters are available in a wide price range depending on **accuracy and functionality**.

Professional systems start at around 3,000 EUR and offer precise measurements, broad measurement ranges, and calibration options suitable for official or research applications.

DIRECT LIGHT COMPARISONS

IN SHORT

- Track changes by counting light sources or analysing images from fixed locations
- Can be supported by citizen science

One method to track changes of light would be the direct imaging from outside or at places within a city like in Tann, Germany (see *Figure 2*).

From these images **just the number of lights can be counted or the luminance measured.** This has been used for tracking the nightly changes of light in New York (Dobler et al. 2015) or at some places in Berlin (J. Meier 2018).

Similarly works a citizen science project called *"NachtLichtBühne"* (2025) where participants counted the numbers of light in certain streets and at certain times during the night.

Figure 2: Example for switch-off of the public lighting in Tann/Rhön at 11 p.m.; top picture before 11 p.m., bottom after 11 p.m.

SATELLITE DATA

IN SHORT

Provides global observations of nighttime light

Allows:
- mapping spatial patterns
- tracking changes over time
- supporting municipal planning

Limited spatial resolution → should be combined with ground-based measurements

The Visible Infrared Imaging Radiometer Suite (VIIRS), onboard the Suomi NPP satellite, provides **global observations of nighttime light** with a ground resolution of about 500 m.
Its Day/Night Band sensor can detect very low levels of visible and near-infrared light, making it particularly valuable for monitoring artificial lighting. It is important to know that the satellite passes only in late night hours (1 – 3 a.m.), when many lights are switched off or reduced, e.g. in Germany.

For local analysis, VIIRS data is commonly used to:

- Map **spatial patterns** of light emissions, showing differences between urban, suburban, and rural areas.
- Track **changes over time**, for example reductions due to energy-saving measures, curfews, or infrastructure upgrades (figures 6 and 7).
- Assess **ecological and environmental impacts,** such as skyglow near natural reserves.
- Support **municipal planning**, by providing an independent, standardized dataset that allows comparison across regions.

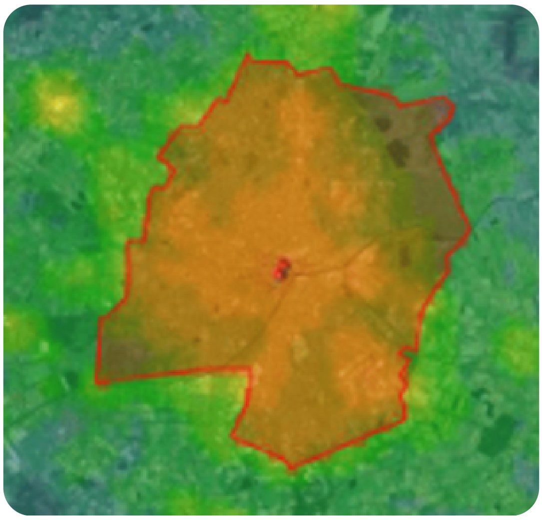


Figure 3: VIIRS data of Oldenburg. The red overlay indicates the city boundary and the area considered. On the map, brighter areas are shown in yellow, while darker green shades represent dimmer, less illuminated regions.

While VIIRS provides a global coverage, its spatial resolution is limited, which means small-scale features (e.g., individual streets or single lamps) cannot be resolved. In addition, the sensor is less sensitive in the blue spectral range, which makes it less effective at capturing the impact of modern white LEDs that emit a significant portion of their light at shorter wavelengths.

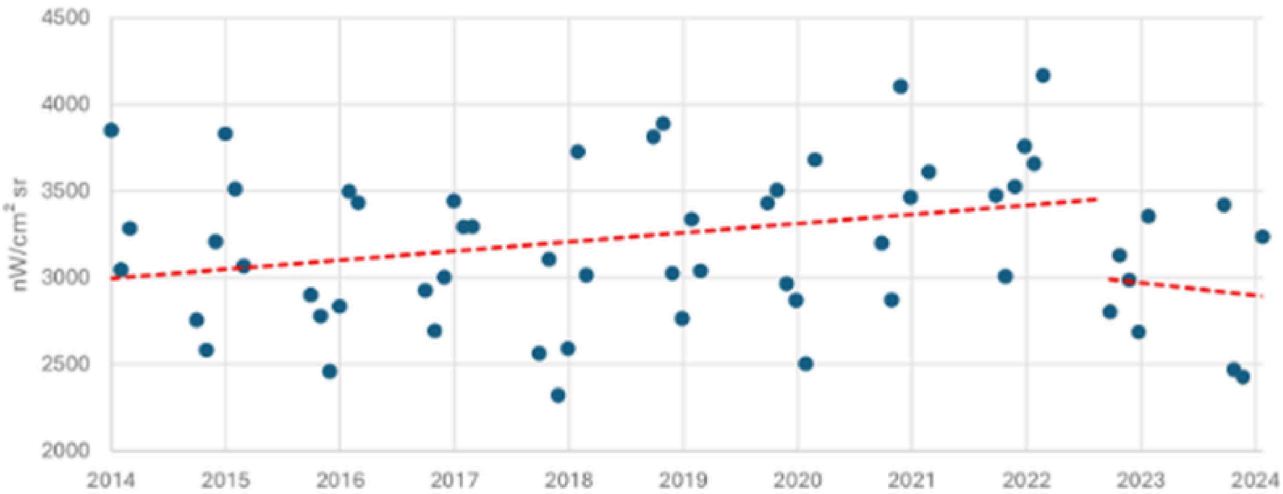


Figure 4: Temporal development of the VIIRS data of Oldenburg. Light emissions of Oldenburg from 2014 to 2024, measured with the VIIRS satellite. Each point represents a single satellite overpass measurement of radiance (in $nW/cm^2 \cdot sr$). The red dashed line shows a trend line indicating the overall change in light emissions during this period. The data suggest a general increase in radiance values from 2014 up to around 2022, followed by a decline in 2023 and early 2024. This variability reflects changes in urban lighting intensity or policies affecting outdoor illumination in Oldenburg.

The VIIRS data measure the direct light from Earth as detected by the satellite. Modelling the scatter in the atmosphere derives the sky brightness, which has been done originally only for the data of 2015 ("World Atlas of light pollution"). An online platform allowing easy access and analysis of VIIRS data is available (LightPollutionMap.info, lighttrends.lightpollutionmap.info, n.d.).

For municipalities, the light pollution data is therefore **best combined with ground-based measurements** to obtain a complete picture of local light emissions.

The VIIRS sensors on the Suomi NPP and NOAA-20 satellites offer **daily global coverage,** providing more frequent observations. The Chinese SDGSAT-1 has a much higher spatial resolution of 40 m and provides colour information.
Its 11-day revisit cycle is not optimal to monitor temporal changes of lighting, especially taking into account cloud cover. SDGSAT data can be accessed online after registration, (SDGSAT, n.d.). An online version (Universidad Complutense de Madrid et al., n.d.) as an overlay over Google Earth maps makes it easy to identify individual strong light emitters.
Contrary to the VIIRS data, most measurements are early (22 solar time) in the night, that even shopping centers or illuminated football places are dominant.

ZENITH SKY BRIGHTNESS

IN SHORT

- brightness of the night sky directly overhead, measures how bright or dark the night sky is
- is often used as a characteristic value for the overall light pollution at a given location

Unit: magnitudes per square arcsecond (mag/arcsec²) or millicandela per square meter (mcd/m²)

Method:
- Measured with handheld or stationary instruments like Sky Quality Meter (SQM)
- Long-term measurements are recommended to exclude variability (clouds, moon, etc.)

This parameter measures the **brightness of the night sky directly overhead** (at the zenith). It is usually expressed in magnitudes per square arcsecond (mag/arcsec²).

Zenith sky brightness is often used to evaluate **overall light pollution in a given location**. Zenith sky brightness is most measured using a so-called Sky Quality Meter (SQM) that is pointed directly upwards at the zenith. Magnitude per square arcsecond (mag/arcsec²) is a way astronomers measure how bright or dark the night sky is.
The term “magnitude” refers to brightness, where lower numbers mean brighter light. An “arcsecond squared” is just a very small patch of sky. Together, mag/arcsec² describes how bright each little patch of sky appears.

For example, a city sky is about 18 mag/arcsec² and looks very bright with only a few stars visible. A suburban sky is around 20 to 21 mag/arcsec², which allows more stars to be seen. A dark rural sky is about 21.5 to 22 mag/arcsec², where the Milky Way is clearly visible.
In short, higher numbers mean a darker sky, while lower numbers mean a brighter, more light-polluted sky.

Though the spectral sensitivity of the SQM does not match the photopic sensitivity, a rough transformation to luminance is possible:

$$luminance\left[\frac{cd}{m^2}\right] \approx 10.8 \times 10^4 \times 10^{-0.4\,magV}$$

The original SQM has a wide measurement angle while the version SQM-L with a lens reduces this angle to 20°. The latter should be used preferentially.

Sky brightness measurement devices can be used as single time handheld measuring devices that provide a measurement at the touch of a button.
However, as the **brightness of the sky is constantly changing** (due to clouds, twilight phases, fog, moon, etc.), this is only a **momentary impression** of the brightness. More accurate comparisons can be made by measuring the brightness **over many nights** (e.g. several months) and looking at the trend.

Various systems of the SQM with different interfaces are intended for **continuous measurements.** For instance, the SQM-L and SQM-DL (*Figure 5*) can record measurements for several months independently using a battery-powered supply. The measuring device is placed in a weatherproof housing, facing towards the zenith.

The DARKER SKY project also uses measuring systems integrated into the Was het donker Network at the University of Groningen (www.washetdonker.nl). In this system, the measuring devices are controlled by a small computer and mobile phone connection and send their data to a central server. This makes the measurement data easily accessible via the internet.

Figure 5: SQM-DL and SQM-L (A. Haenel)

Figure 6: The housing of SQM-DLs and SQM-Ls.

Apart from the widely used SQM systems (Unihedron, n.d.), **several other instruments** can be employed to measure zenith sky brightness, most notably the TESS devices (e.g. TESS-W, TESS-P, TESS-4C) developed by the Stars4All Foundation (Stars4All Foundation, n.d.).

These instruments differ in their design, ranging from portable single-channel sensors to all-sky and multi-band systems, as well as in their connectivity and measurement accuracy. SQM and TESS devices typically achieve accuracies on the order of ±(0.05–0.1) mag/arcsec^2 and are widely used in scientific studies and monitoring networks.

Figure 7 shows an **exemplary sky brightness measurement** during a cloud covered and a clear night with a TESS-W at the village Tann in the International Dark Sky Reserve Rhön.
Over the course of the night, the sky brightness decreases as darkness sets in and increases again towards morning. More details in the caption of *Figure 7*.

The darkest sky conditions (highest magnitude numbers) observed at that location can be used as a **representative measure** of sky brightness and allows for comparison between different locations.

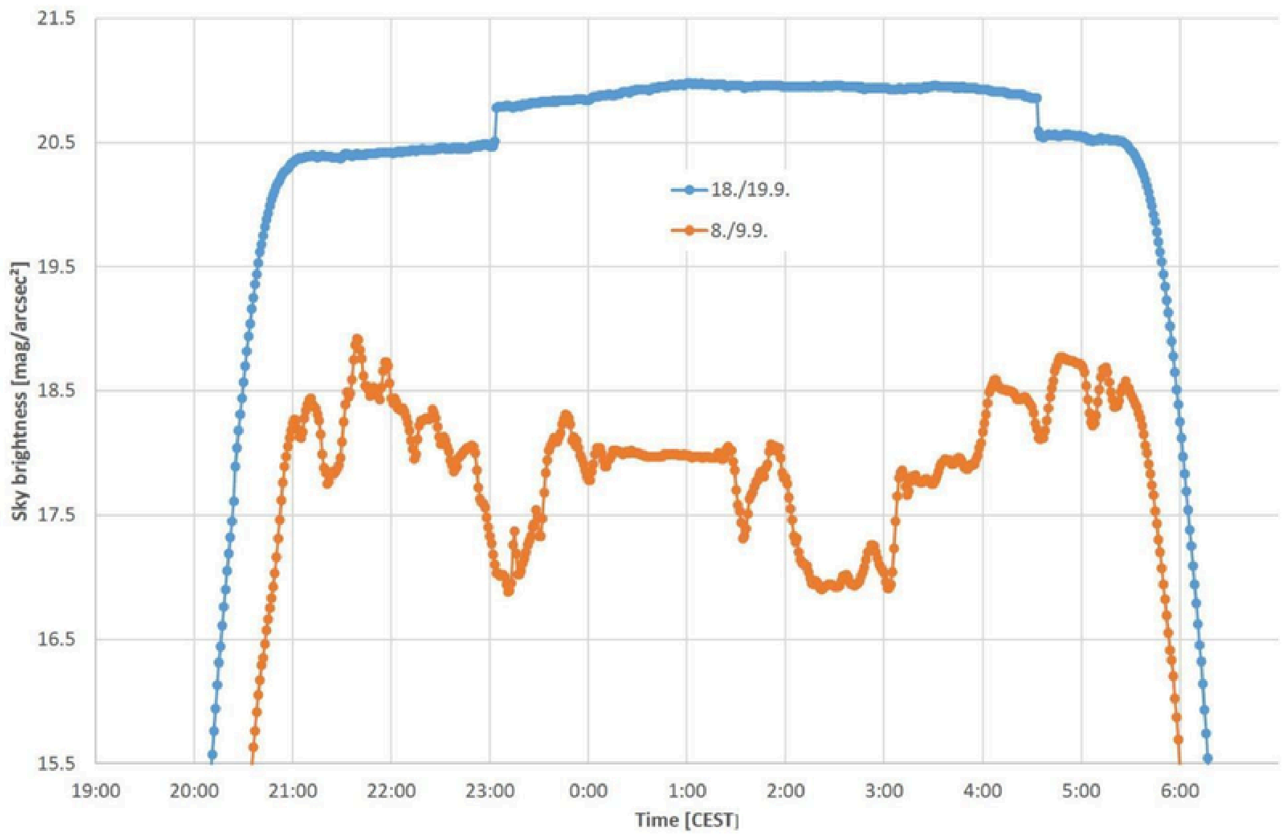


Figure 7: Typical sky brightness graph of TESS-W measurements (himmelsmonitoring.de) of two different nights in Tann/Rhön. Orange graph: clouds and a bright moon lit night lead to strong variations of the sky brightness; blue graph: a clear moonless night shows the effect of switching off the public lighting at 11 p.m. and switch on at 4:30 a.m . The higher the value of the sky brightness, the darker the sky.

Table 5 provides an overview of **typical night sky brightness** values in mag/arcsec² for different environments and illustrates how these values correspond to the visual appearance of the night sky as perceived by the human eye.

ENVIRONMENT	TYPICAL mag/arcsec2	WHAT THE SKY LOOKS LIKE
Bright city centre	16 - 18	Sky looks grey or orange; only the brightest stars and planets visible
Inner suburbs	18 – 19.5	Some stars visible, but the Milky Way is completely hidden
Outer suburbs / small town	19.5 – 20.5	Hundreds of stars visible; faint Milky Way patches may not be
Rural area	20.5 – 21.2	Milky Way visible but less detailed; good for casual stargazing
Dark Sky-Park / Wilderness	21.2 – 21.7	Sky is very dark; Milky Way is bright, detailed, and striking
Exceptional sites (mountains, deserts)	> 21.7	Extremely dart; zodiacal light and faint airglow may be visible

Table 4: Summary of typical sky brightness values [based on Haenel et al, 2018).

SKY BRIGHTNESS

IN SHORT

- Measures distribution of light across the sky

Unit:
same units as zenith brightness; magnitudes per square arcsecond ($mag/arcsec^2$) or millicandela per square meter (mcd/m^2)

Method:
- With all-sky cameras
- measuring distribution of brightness across the entire night sky, allowing an assessment of how evenly or unevenly light pollution affects different parts of the sky

More generally, sky brightness refers to the **luminous intensity of the night sky across different parts of the hemisphere**. It can be measured in the same units as zenith brightness but provides a broader picture, as the sky is usually not equally bright in all directions.

Typically, sky brightness is measured with **all-sky cameras**. These instruments capture the distribution of brightness across the entire night sky, allowing an assessment of how evenly or unevenly light pollution affects different parts of the sky.
All-sky cameras use fisheye or ultra-wide-angle lenses to capture the entire sky in a single image, allowing measurement of brightness across the sky in units like $mag/arcsec^2$, cd/m^2 or even mcd/m^2 (milli cd/m^2).

These cameras require **careful calibration**, using flat fields, and reference stars to correct for sensor response and lens effects (vignetting). They can be monochromatic to measure overall brightness or multispectral to distinguish contributions from different natural (e.g. airglow) or artificial light sources, such as LEDs or sodium lamps.

An example of such an instrument is a commercial digital single lens camera with a fisheye lens for high-sensitivity imaging (*Figure 8*). This system can be calibrated (in a light laboratory or with stellar magnitudes) and the data is analyzed e.g. with the Sky Quality Camera (SQC) software (*Figure 9*). This commercial software SQC was developed by Andrej Mohar from Euromix Ltd, Slovenia.

Figure 8: Sky Quality Camera (SQC, Canon 6D camera and Sigma fish-eye lens) installed in a protective housing.

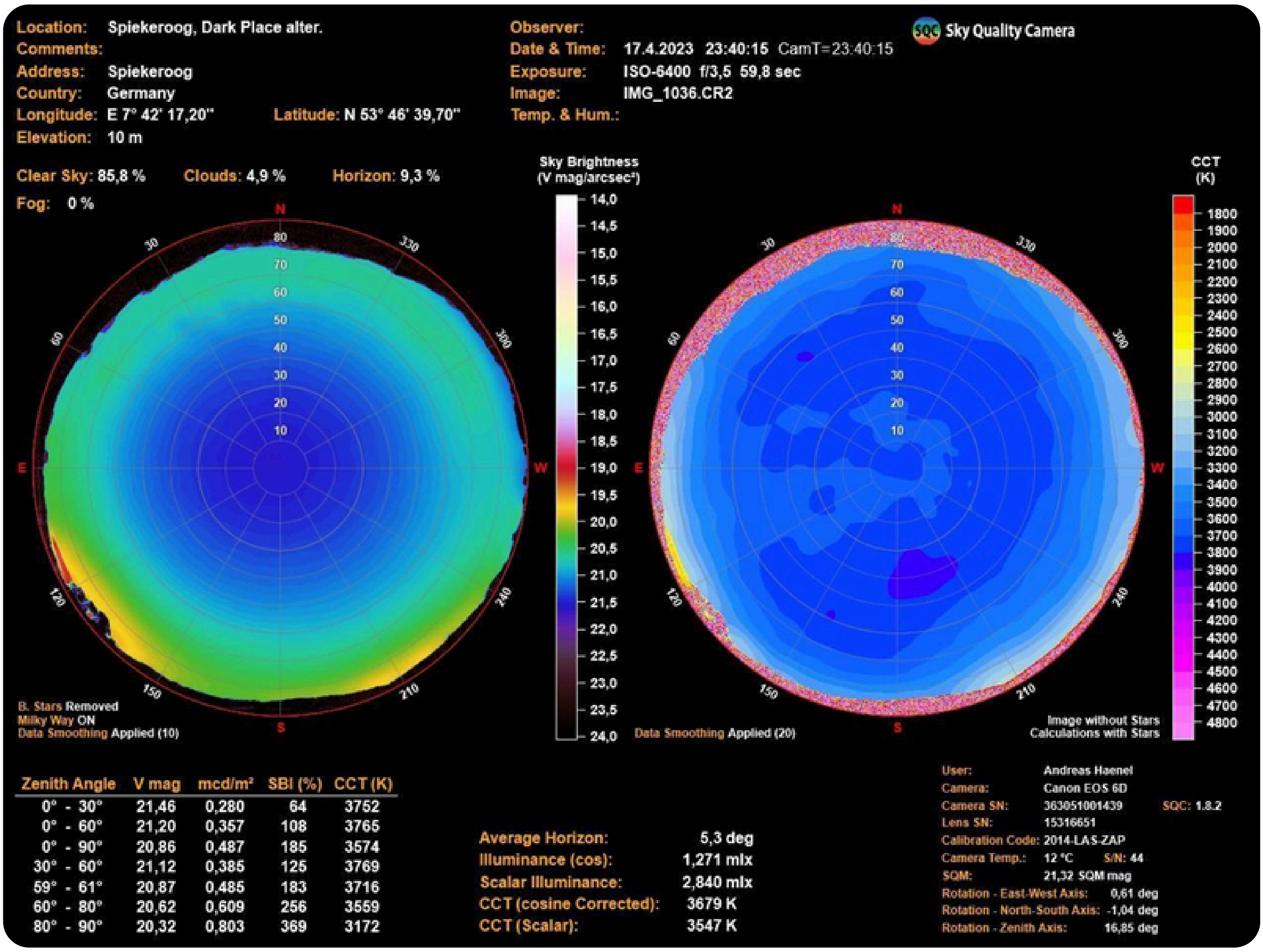


Figure 9: Typical analysis of SQC data utilizing the SQC software, distribution of the sky brightness (left) and CCT (right) over the sky as well as different characteristic numbers are given.

After capturing images, a software generates **2D brightness maps**, which can provide zenith values, horizon values, and gradients of light pollution. By taking repeated images over the night, all-sky cameras can also track temporal variations caused by clouds, lighting schedules, or seasonal changes.

Advantages include high spatial resolution, full-sky coverage, and the ability to detect spectral differences. **Limitations** involve the need for careful calibration, sensitivity to weather conditions, and restriction to local-scale observations.
Similar reduction possibilities offer the free software DiCaLum from Zoltan Kollath (www.dicalum.eu).

COMPARING THE DIFFERENT METHODS:

Earth based zenith measurements allow to detect light changes during one night, especially with stable clear weather conditions. However, quantitative information about artificial lighting is difficult to derive as the scattering in the atmosphere has to be modeled, therefore especially long-term changes are difficult to detect.
Direct imaging and satellite measurements detecting the direct light are ideal to track lighting changes over larger areas on Earth and long-term changes if the detectors are well calibrated.

4 PLANNING ARTIFICIAL LIGHT AT NIGHT

>> Municipalities can achieve more environmentally friendly lighting with a few **simple and cost-effective measures.**

These include:
- Adjusting light levels to actual needs
- Directing fixtures to areas of use to avoid unnecessary spill light
- Using warmer colour temperatures with less blue content in spectra
- Applying time controls or dimming during low-traffic hours.

Such actions not only improve residents' **quality of life and reduce ecological impacts** but also **lower energy consumption and operating costs**.

These recommendations are mainly based on:
- The **Five Principles for Responsible Outdoor Lighting** by Dark Sky International (also applied for the certification of International Dark Sky Places; International Dark-Sky Association, n.d.)
- **Recommendations for new and retrofit installations of outdoor lighting** (Leitfaden zur Neugestaltung und Umrüstung von Außenbeleuchtungsanlagen, BfN-Skript 543; Bundesamt für Naturschutz [BfN], 2019)
- **Premium Light Pro, LED street lighting, procurement & design guidelines** (European Commission, 2017)

More **detailed checklists** are developed with the biosphere reserve of the Lower Saxony Wadden Sea National Park and the German project "Sternenfunkeln über dem Wattenmeer" (Nationalpark Wattenmeer 2023, 2026).

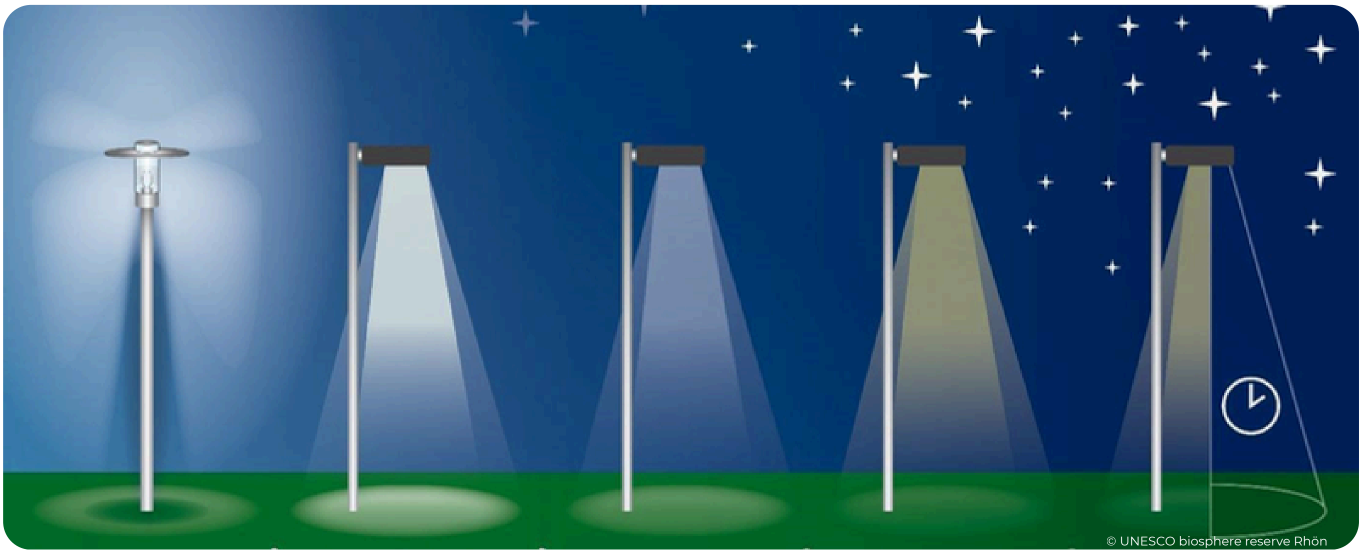


Figure 10: Comparison of different lighting situations. From left to right: 1. badly shielded, blue-white light; 2. Fully shielded, blue-white light, high level; 3. Lower luminous flux; 4. Fully shielded, warm white colour, low lighting level, switch-off (Source: UNESCO biosphere reserve Rhön)

In installing artificial outdoor light, the following five considerations concerning environmental aspects should be considered and discussed in more detail.

1. IS ARTIFICIAL LIGHT REALLY NECESSARY?

Will it be justified by the **number of users**?
Could **alternative methods** (like retroreflectors, self-luminous colour, white markings) be sufficient?

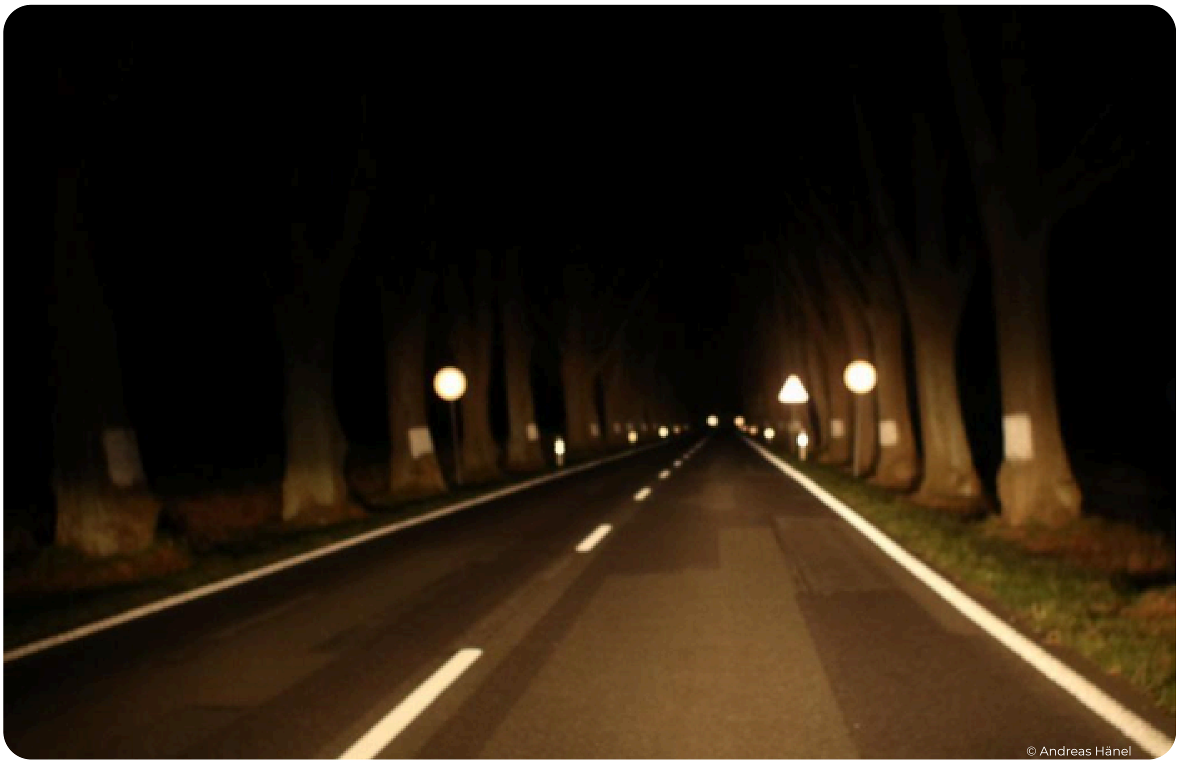


Figure 11: Good reflective markings allow to recognize the course of a street very well without additional installed artificial light (Source: A. Haenel).

2. HOW MUCH LIGHT IS NEEDED?

For public lighting often **standards** (e.g. EN 12301) are applied, which are **not mandatory in all CEN countries according to local legislative structure.**

The lighting levels are defined by lighting classes, that indicate the use of the road:
- M for main roads,
- C for road users in conflict regions and
- P for pedestrians and cyclists in residential roads

As minimum levels, upper limits are not defined expressively. Subclasses depend mainly on street geometry, type of traffic use, speed limit, travel volume and composition, and more. The values that are defined in M class roads are mean values and uniformity of luminance (cd/m²), for C and P classes mean values and uniformity of illuminance (lx). The choice of the lighting class should be considered carefully and in accordance with the needs of users and environment.

Too high lighting levels that **exceed the luminance or illuminance values of the lighting class distinctly should be avoided**, not only with regards to nature protection, but also to energy consumption. However, recurrent energy related measures, like the "Annual Energy Consumption Indicator" (AECI) and "Power Density Indicator" (PDI) as defined in EN 13201-5 are applied only rarely to date.

Further European Standards (e.g. EN 12464-2, outdoor working places, EN 12193 Sports places) or national regulations (Workplace Ordinance in Germany, "Arbeitsstättenverordnung") might be applicable.

3. WHEN WILL ARTIFICIAL LIGHT BE NEEDED?

Lighting is necessary, when people use or may use a space especially as pedestrian or cyclist. However, this use must be **evaluated** and is of **different intensity** during various times of night and year.

A good lighting installation emits light adapted to its use. It may emit light according to lighting classes through busy early evening hours, may be dimmed down or switched-off during night when there are no or only very few users.
Each municipality or city district has a specific traffic pattern and should evaluate areas according to its use very carefully.

While **dimming** is possible with LED lamp installations, it is more difficult with gas discharge lamps (e.g. high-pressure sodium lamps), though technical solutions do exist. The technically easiest solution then is to **switch off** the light, a strategy employed in larger cities such as many in France. Another option is to switch off **every second fixture**, but reduces the uniformity of the illumination compared to a homogeneously dimmed installation. Dimming adjusted throughout the night according to the actual traffic situation is demonstrated by the city of Springe near Hannover (*Figure 12* and *Figure 13*).

Figure 12: Reducing the lighting levels in a shopping street in Springe (source: A. Haenel)

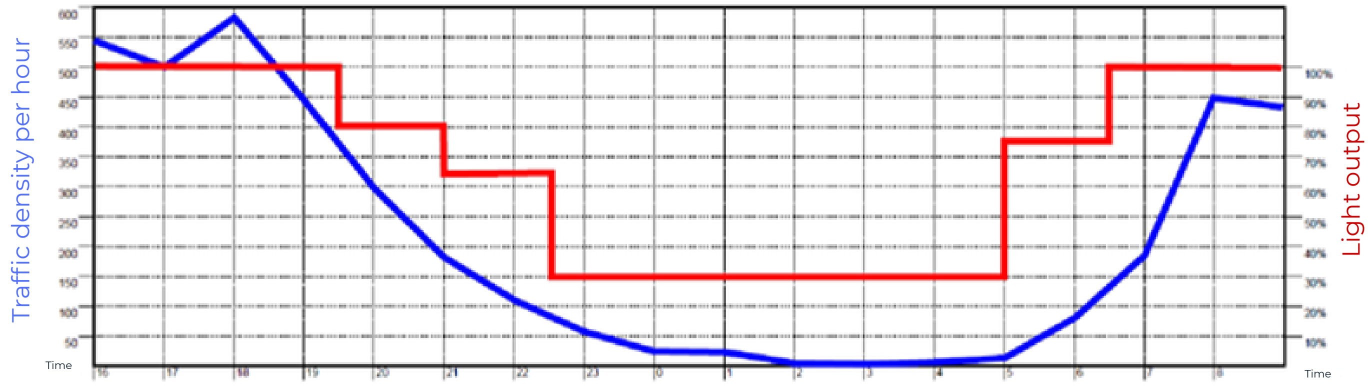


Figure 13: Traffic density (blue) and accordingly reduced street lighting levels (red) during night hours in Springe, Germany (Stadt Springe, n.d.)

Another adaptive method is to dim or switch off lights and activate them with **motion sensors.** However, the installation and operating costs (including licences and mobile connections) are still relatively high (in 2026).

In addition to positive environmental effects, dimming and/or switching off are the most important factors in reducing energy use and costs at large scale for municipalities.

4. WHERE IS ARTIFICIAL LIGHT NEEDED?

Artificial lighting should only be installed where it is truly necessary.

All luminaires must be carefully oriented towards the areas that require illumination, and especially no upward light should be emitted.

Limiting the emission to angles below e.g. 10° under the horizontal line through the lamp fixture is preferred and also limits the glare of the luminaire (*Figure 14*).

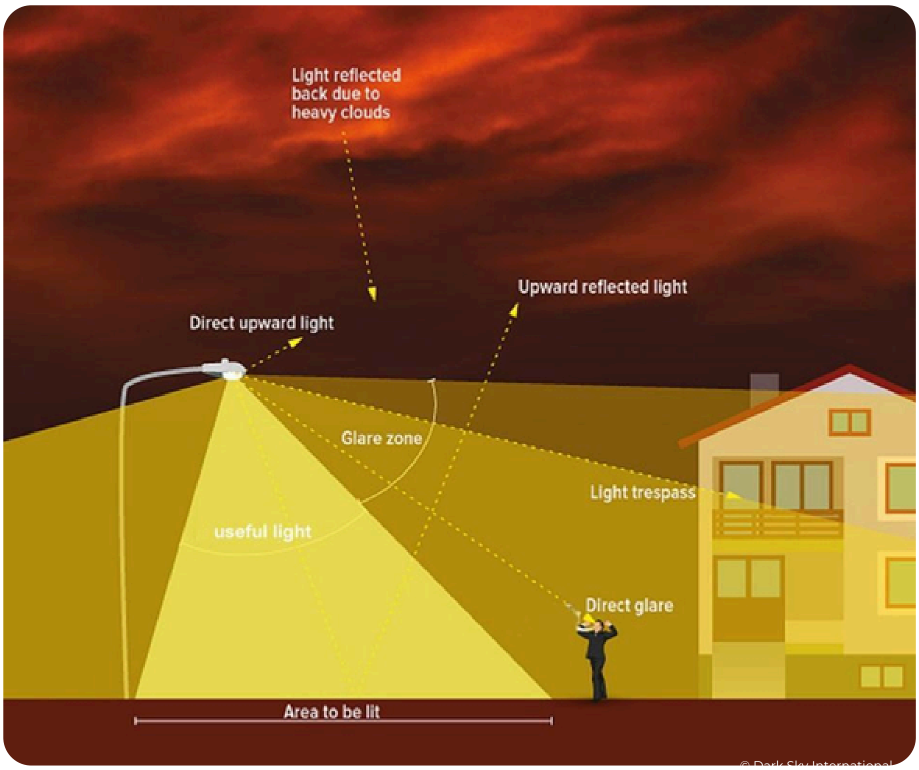


Figure 14: Illustration of intended and unintended light emissions. The diagram shows useful light directed toward the target area (useful light), wasted light emitted outside the intended area, and disturbing light causing unwanted skyglow—both direct and indirect components. Additionally, it highlights unwanted brightening of surrounding surfaces (Dark Sky International).

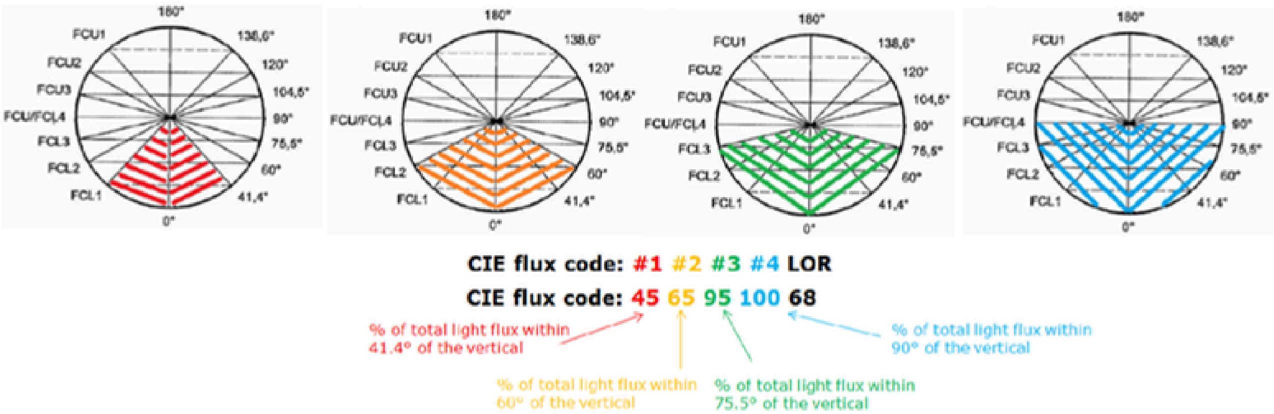
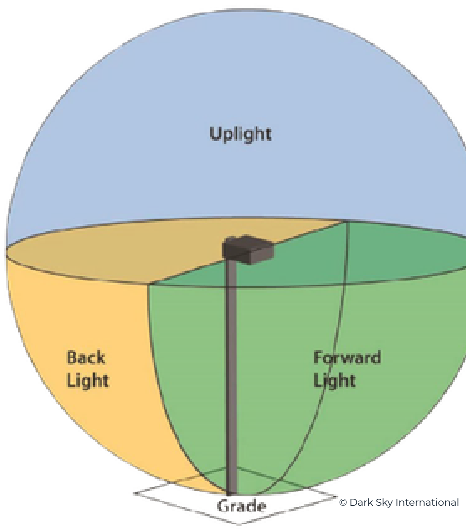


Figure 15: Using the CEN/CIE flux code for defining illuminated zones. The lamp is in the central position of the circle (Donatello et al., 2019).

The direction of light in outdoor lighting installations can be described by different parameters:

- **Upward Light Ratio (ULR)** is the percentage of light emitted by an installed luminaire above the horizontal line through the luminaire. The ideal value is 0%, and it should in any case remain below 1%.
- **The luminous intensity class for physiological glare rating G** as described in the informative Annex A of EN 13201-2. The aim of the G class is to limit the glare of a luminaire by quantifying the luminous intensity emitted in specific directions. Only class G6 permits no light emitted above the horizontal of the luminaire.
- The distribution of the luminous flux of a luminaire (mainly for indoor lighting, but also applied to outdoor lighting) can be described by the "**CEN/CIE luminous flux code**" (EN 13032-2). This code consists of 8 ratios of the relative flux distribution as described in *Figure 15*. For luminaires emitting only downwards, the first 5 ratios are sufficient.
- Limiting the **vertical emission angles** more detailed: e.g. in the French legislation 95% of the total luminous flux shall be emitted within the FCL3 zone of the CEN/CIE flux code (second graph from left in *Figure 15*).



- **Utilance** describes the ratio of luminous flux on the area to be used compared to the total luminous flux emitted.
- **BUG ratio** (backlight – uplight – glare), which is mainly used in the USA. Uplight luminous flux should ideally be 0, backlight flux should be as low as possible (*Figure 16*).

Figure 16: Light distribution of a luminaire demonstrating the B(ackward U(pward) F(orward) ratio (source: Dark Sky International).

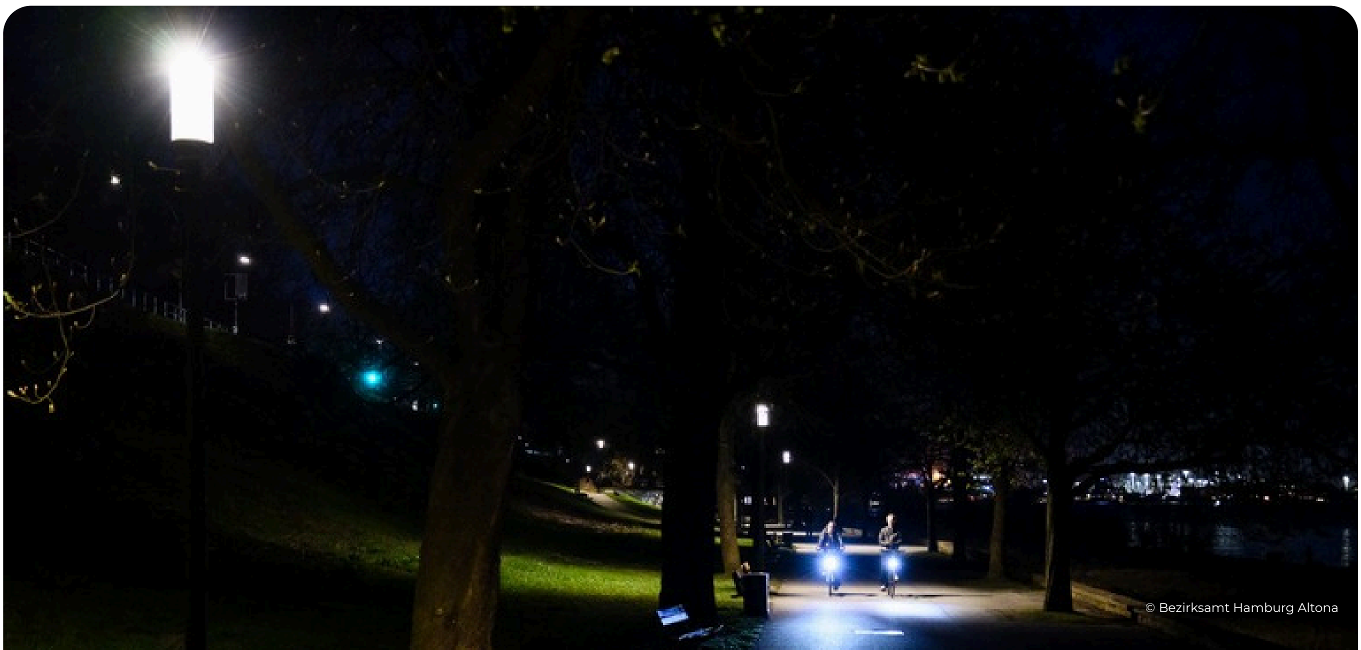
To prevent glare, light distribution needs to be thoughtfully designed. Light sources should always be **fully shielded**, and if required, **additional shades or gobo projections** can be used. Research projects, such as the AUBE project in Germany, have shown that specially designed luminaires can significantly reduce insect attraction (see *Figure 17*, Dietenberger et al. 2024).

For many fixtures that are installed in an inclined position, **upward light** can be reduced by **inclining the fixture to the horizontal**.

Backward light, about which people living behind luminaires complain, may be reduced **using shields** offered by many manufacturers.

Figure 17: The effect of specially tailored luminaires, that direct light only to the area to be illuminated compared to the old installation (right) in the same street (AUBE project in Nature Park Westhavelland, source: A. Haenel).

Finally, it is important to **consider the real need:** since car headlights already illuminate roadways, municipal lighting may be **more relevant for pedestrian and cycling areas**—although cyclists should have their own lighting which is meanwhile brighter than ever before.
Facade illumination should avoid any light that is not targeted to the area intended to be lit. This, as well as the exclusion of windows or exit holes for bats, can be avoided by special projection techniques (so called Gobos).



5. LOW BLUE CONTENT – “WARM” LIGHTING COLOURS?

As ultraviolet and blue light contributions (as part of white light) are **especially detrimental to many species**, especially insects, these should be reduced. On the other hand, a small blue fraction is essential for colour recognition in human vision, which is needed for users of the space.

- the fraction of blue light of a specified wavelength region compared to the whole visible spectrum is the most accurate method
- the correlated colour temperature CCT compared to a thermal Planckian radiator (like the sun or a tungsram lamp). This is more a rough estimation as many artificial light sources except tungsram lamps or non-Planckian radiators. Low CCT corresponds to less blue content.

The generally low ecological impact of sodium high pressure lamps has been confirmed in many studies. **Their blue content of about 7 % of all visible light under a wavelength of 500 nanometers (nm) could be applied to LED lighting**. This corresponds roughly to a correlated colour temperature of 2200 K. This warm white light appears more pleasant and less glary to many people.

Already installed high CCT (e.g. 4000 K) can be **transformed to warmer light by using colour conversion filters**, like yellow-orange foils or coloured silicone lenses. However, this should only serve as an **interim solution**.

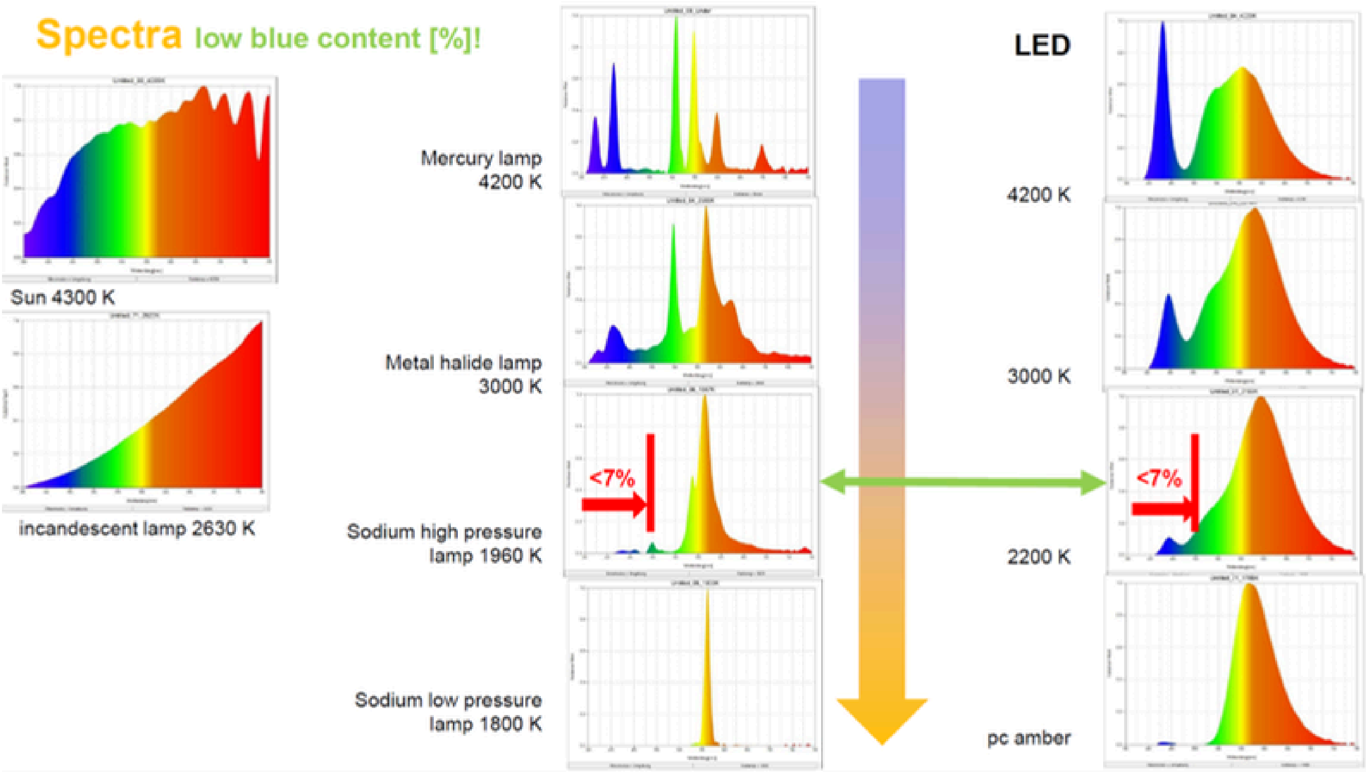


Figure 18: Spectral distributions and CCT of different light sources. As orientation the blue content below a wavelength of 500 nm of a sodium high pressure lamp should be less than 7% of all visible light (A. Haenel).

REFERENCES

Bundesamt für Naturschutz (BfN). (2019). Leitfaden zur Neugestaltung und Umrüstung von Außenbeleuchtungsanlagen (BfN-Skript 543). https://www.bfn.de/publikationen/bfn-schriften/bfn-schriften-543-leitfaden-zur-neugestaltung-und-umruestung-von

Dietenberger, M., Jechow, A., Kalinkat, G. et al. (2024): Reducing the fatal attraction of nocturnal insects using tailored and shielded road lights. Commun Biol 7, 671 (2024). https://doi.org/10.1038/s42003-024-06304-4

Dobler, G., Ghandehari, M., Koonin, S. E., Nazari, R., Patrinos, A., Sharma, M. S., Tafvizi, A., Vo, H. T., & Wurtele, J. S. (2015). Dynamics of the urban lightscape. Information Systems, 54, 115–126. https://doi.org/10.1016/j.is.2015.06.002

Donatello, S., Rodríguez Quintero, R., Gama Caldas, M., Wolf, O., Van Tichelen, P., Van Hoof, V., Geerken, T., & Vito. (2019). Revision of the EU Green Public Procurement criteria for road lighting and traffic signals (EUR 29631 EN). Publications Office of the European Union. https://doi.org/10.2760/372897

European Commission. (2017). Premium Light Pro, LED street lighting, procurement & design guidelines. https://ec.europa.eu/research/participants/documents/downloadPublic/OUxSb3JmQUw5K2w5VExndTdaOHBQYmJUVGozbVM0WkxydG5OcU1kRTU1bHY2OWlxd3JzemZRPT0=/attachment/VFEyQTQ4M3ptUWM5Tng2NWpzb1VsaU9VQ243alhhaXA=

Hänel, A., Posch, T., Ribas, S. J., Aubé, M., Duriscoe, D., Jechow, A., ... & Kyba, C. C. (2018). Measuring night sky brightness: methods and challenges. Journal of Quantitative Spectroscopy and Radiative Transfer, 205, 278-290. https://doi.org/10.1016/j.jqsrt.2017.09.008

International Dark-Sky Association. (n.d.). The Five Principles for Responsible Outdoor Lighting. https://darksky.org/what-we-do/international-dark-sky-places/apply/

LightTrends. (n.d.). Light pollution map. https://lighttrends.lightpollutionmap.info

Meier, J. M. (2018). Temporal profiles of urban lighting: Proposal for a research design and first results from three sites in Berlin. International Journal of Sustainable Lighting, 20(1). https://doi.org/10.26607/ijsl.v19i2.82

Nationalpark Wattenmeer. (2023). Licht für Kommunen. https://www.nationalpark-wattenmeer.de/wp-content/uploads/2023/11/Bro_LichtFuerKommunen_202311_web.pdf

Roulet, Y., Dauvergne, X., & Gallet, S. (2026). Artificial light at night and terrestrial fauna: A review on research trends and knowledge gaps. Biological Conservation, 321, 111963. https://doi.org/10.1016/j.biocon.2026.111963

Schröter-Schlaack, C.; Revermann, C.; Schulte-Römer, N. (2020) Lichtverschmutzung – Ausmaß, gesellschaftliche und ökologische Auswirkungen sowie Handlungsansätze. Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB). doi:10.5445/IR/1000121964

SDGSAT. (n.d.). Satellite data portal. https://www.sdgsat.ac.cn/satellite/data

Stadt Springe. (n.d.). Startseite. https://www.springe.de/

Stars4All Foundation. (n.d.). TESS: Tools for environmental sky survey. https://foundation.stars4all.eu/tess/

Unihedron. (n.d.). Sky Quality Meter. https://www.unihedron.com/projects/darksky/

Universidad Complutense de Madrid, University of Exeter, Plan-B, & International Research Center of Big Data for Sustainable Development Goals (CBAS). (n.d.). SDGSAT EU visual [Web application]. https://pmisson.users.earthengine.app/view/sdgsat-eu-visual

ABOUT

Authors in alphabetical order:
Dr. Andreas Hänel
Working Group Dark Sky der Vereinigung der Sternfreude e.V.

Prof. Dr.-Ing. Carolin Liedtke
HAW Hamburg University of Applied Science

Athleen Selma Rietze
Carl von Ossietzky Universität Oldenburg

Yoann Roulet
Université de Bretagne Occidentale

Jan-Willem van Kruyssen
Landmakers Cooperatie U.A.

CONTACT

Project Management:
Arthur Renaud, Arthur.renaud@univ-brest.fr

LEARN MORE ABOUT DARKER SKY

- www.interregnorthsea.eu/darker-sky
- linkedin.com/company/darkersky-ns
- youtube.com/@darkersky-interregnorthsea
- Light Pollution Knowledege Hub
  >> *Join to find all DARKER SKY fact sheets, guides and more resources while connecting with stakeholders across the North Sea Region!*

Use of AI:
AI was used support language editing and improve readability. All technical and scientific content was reviewed and validated by the project experts.

DARKER SKY | Interreg North Sea | Co-funded by the European Union