



Article Development of an Indicator System for Local Governments to Plan and Evaluate Sustainable Outdoor Lighting

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Abstract: Outdoor lighting offers many benefits to its users and is often considered a necessity for an active lifestyle when living in modern society. Sustainable outdoor lighting should fulfil the functional needs of the users, be cost- and energy-efficient, and result in minimal environmental impact. So far, a limited number of studies have been able to present clear strategies on how to plan and use outdoor lighting to ensure that it contributes towards sustainable development. Therefore, this study aimed to answer the following questions: (1) How many of the previously established sustainability indicators are already used by municipalities in their lighting planning? (2) Which types of indicators are not used by municipalities? Another aim of the study was to further develop the framework of sustainability indicators by adding new indicators that were identified from lighting plans of Swedish municipalities and the existing literature. In this study, lighting master plans from 16 randomly chosen Swedish municipalities with varying population sizes were analyzed. The results show that few sustainable indicators are used by the municipalities' lighting plans, especially in the social dimension. The existing framework of sustainability indicators was developed by adding new indicators. Furthermore, 28 new indicators were identified, eight originated from new studies and the literature, and 20 originated from the municipalities' lighting master plans. This study shows that there is a need for guidelines and recommendations for working with outdoor lighting from a sustainability perspective, especially in the social dimension of sustainability, where most of the new indicators were identified.

Keywords: exterior; planning; municipal; streetlight; ecological; environmental; economic; impact; light pollution; safety; visibility; social

1. Introduction

Outdoor lighting offers many benefits to its users and is often considered a necessity for an active lifestyle when living in modern society. The benefits of outdoor lighting for users and society are plentiful and include, for example, increased safety, attractive outdoor environments, visibility and comfort, promotion of outdoor activities, and reduced fear of crime [1]. However, the use of artificial lighting at night in the outdoor environment also has many negative indirect effects, such as high energy consumption due to long operating hours and high wattage needed to sustain visibility and safety for users, resulting in high costs for the lighting owners as well as contributing to the emission of CO_2 and increasing global climate change [2]. Other negative indirect effects include light pollution, defined as the "sum total of all adverse effects of artificial light" by the International Commission of Illumination (CIE) [3], impacts on humans and ecosystems [4], and environmental impact from the various stages of the life cycle of the luminaire and light source. The negative impacts of artificial light at night have been attracting more and more attention during recent decades, as several studies have shown that light pollution is increasing globally, e.g., [5,6], and that artificial light at night causes unwanted ecological impacts on ecosystems [7] and biodiversity [8].



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Copyright: © 2021 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Sustainable outdoor lighting should fulfil the functional needs of the users, be costand energy-efficient, and result in minimal environmental impact. The human functional needs of outdoor lighting have been studied from a vast range of aspects, such as being safe and feeling safe, traffic safety, obstacle detection, and facial recognition, to mention a few. For comprehensive overviews of the functional needs of users, see, for example, lighting for pedestrians [9,10], benefits of outdoor lighting [1], and road lighting for drivers and pedestrians [11]. Negative impacts in terms of light pollution; ecological impacts; global climate change; and unwanted environmental impacts in the life cycle of light sources, for example, the depletion of precious metals, hinder the sustainable development of outdoor lighting. For successful sustainable development of outdoor lighting, many aspects need to be considered simultaneously and thoroughly. Unfortunately, only a limited number of studies have so far been able to present clear strategies on how to plan and use outdoor lighting in a full holistic view, considering several aspects simultaneously, to ensure that it contributes towards sustainable development [12,13].

Sustainable development was originally defined in the Brundtland report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [14]. The 2030 Agenda (Agenda 2030) for a Sustainable Development was adopted by all United Nations members in 2015 [15] and is based on 17 sustainable development goals (SDGs). These are, for example, good health and wellbeing (SDG 3), gender equality (SDG 5), affordable and clean energy (SDG 7), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15). Many of the SDGs can be affected by decisions concerning outdoor lighting, which motivates the integration of sustainable development in the planning, operation, and maintenance of the lighting.

The first study identifying aspects of sustainable development for outdoor lighting was published in 2015 and consists of a framework of identified sustainability indicators for outdoor lighting that allows for an overview and prioritization in line with sustainability goals [12]. The framework consists of 84 sustainable indicators divided into the three dimensions of sustainability—ecology and environment, economy, and social and society. Most of the indicators in the framework are theoretically possible to use for decision-making by local governments, such as municipalities, but it is likely that the implementation will be difficult due to the lack of information on quantitative data for the indicators. Indicators from state-of-the-art light-emitting diode (LED) lighting will not be easy to use due to a lack of scientific knowledge in certain areas, and for several indicators and aspects, there exist no standardized metrics for measuring or monitoring. This includes many ecological and environmental indicators (e.g., ecological light pollution) as well as indicators from the social and societal sustainability dimensions (e.g., indicators of well-being or human health) [12]. Even though much research has been conducted in recent years, for example, on the ecological impact of artificial light at night, the use of indicators has not yet been established by any international organization, such as CIE. However, there is now ongoing work in technical committees (TCs) for the development of metrics for obtrusive light from colorful and dynamic lighting systems (TC4-58) and providing guidance on ways to minimize the effects of artificial lighting on the natural environment (TC4-61). For indicators already in use, such as cost of installations and life length, it can be anticipated that there will be low resistance to the start of their successful use.

There are limited tools that can be used to evaluate the sustainable development of outdoor lighting. A study that suggested a decision supporting systems' assessment for street lighting restricted the assessment to light pollution and energy performance indicators [16]. Another study that presented a multicriteria assessment with the aim of finding the most beneficial and sustainable lighting solution used indicators representing the luminous environment, light pollution, and energy efficiency to evaluate four groups of outdoor lighting types [17]. A third study, which aimed to propose a method for assessing public tenders of LED lighting based on multiple decision-making criteria, restricted the environmental impact assessment evaluation to life cycle analysis (LCA) [18]. However, currently, no proposed assessment method has used any indicators from the social sustainability dimensions. These approaches may be suitable from a more technical engineering perspective but will not be useful for local governments that strive towards the goals of Agenda 2030 and therefore need to fully integrate all relevant aspects of sustainable development, including, for example, ecological impacts and social sustainability.

The current framework of sustainability indicators has not been evaluated from the perspective of what can be used by officials or decision-makers in municipalities or local governments or from the perspective of what factors or indicators are prioritized and emphasized in lighting master planning. Spatial planning for dark hours in local governments or municipalities is usually handled within lighting master plans or lighting programs. Currently, there exist no established definitions or approaches for lighting master plans, but they should consist of a strategic planning document [19]. According to the technical report CIE 234:2019 "A Guide to Urban Lighting Masterplanning", the primary objective of the lighting master plan is to: "identify all forms of lighting that contribute to the urban nightscape and to ensure that these are provided and operated in a manner which creates a balanced overall ambience with respect to users' activities and energetic/environmental aspects" [20]. To support the primary objective, the lighting master plan should include the visual objective, legislative, managerial, and economic aspects. To achieve a holistic (or sustainable) design of a lighting master plan, considerations must encompass various aspects for functionality, expression, and the impact on the environment [20].

Hitherto, no previous study has investigated how successful local governments are in integrating strategic goals and actions towards sustainable development or the implementation of a holistic design in the planning or evaluation of outdoor lighting by, for example, analyzing municipal lighting master plans. Nevertheless, such an investigation is of high importance since goals for sustainable development may have a range of various interactions, which may lead to conflicting results between goals when taking action. This is demonstrated in a study where the framework was used for investigating the interactions between sustainable development and energy performance [13]. It was found that most of the interactions were synergistic but that tradeoffs could be found in the economic and social dimensions [13]. For example, increasing illuminance to improve traffic safety or perceptions of safety (as is often used as motivations for improvements by local governments) will result in a tradeoff between energy performance and sustainable development because increased social sustainability will lead to increased energy consumption. A study investigating the effects of reduced road lighting by switch-off, part-night lighting, dimming, and white light in England and Wales revealed no significant impact on collisions and little evidence of harmful effects on crime [21], indicating that it is possible to reduce lighting without a negative impact on social sustainability. Hence, it might therefore be an unjustified action to increase illumination levels when the aim is to increase social sustainability.

Improved knowledge of synergies or tradeoffs between sustainability indicators will help local governments improve their planning policies for outdoor lighting and will assist in prioritizing goals that both will increase energy performance and will support the objective of sustainable development.

Therefore, this study aimed to answer the following questions:

- How many of the previously established sustainability indicators are already used by municipalities in their lighting planning?
- Which types of indicators are not used by municipalities?

Another aim of this study was to further develop the framework of sustainability indicators by adding new indicators that were identified from lighting master plans of Swedish municipalities or indicators that are supported by scientific progress that were developed since the publication of the original framework.

In this study, lighting master plans from 16 randomly chosen Swedish municipalities with varying population sizes were analyzed. The content was matched against the

sustainability indicators in the original theoretical framework, and new indicators were extracted. Scientific literature in the specific areas of the three dimensions of sustainability was reviewed to find new indicators that could be included in the framework.

This paper is organized as follows. The framework of sustainability indicators is described in Section 2. The materials and methods are described in Section 3, and the results are presented in Section 4. The results obtained are discussed and presented in detail in Section 5.

2. Sustainability Measurement Framework and Indicators

As mentioned above, the only existing sustainability framework for outdoor lighting was published in 2015. It contains 54 sustainability indicators in the environmental and ecological dimension, six sustainability indicators in the economic dimension, and 24 sustainability indicators in the social dimension (Figure 1). For each dimension, several areas and sustainability indicators have been identified. However, since sustainability indicators in different areas can be the same, there is some overlap within the framework. For example, a dimming schedule will reduce ecological impact, light pollution, energy consumption, and cost. In the framework, light pollution resulting in ecological impact is separated from "astronomical" light pollution. The reason for this separation is that not all light sources will result in sky glow but the ecological impact can still be significant. However, light pollution is often used in the literature without this distinction. Light pollution resulting in adverse impacts on humans, such as glare, for example, is included under social sustainability. The framework was originally established based on LED and solid-state lighting (SSL), and because these light sources are still rather new, some knowledge gaps were identified. Hence, the original framework should be viewed as a preliminary guideline that successively will need improvements rather than as a final tool.



Figure 1. The framework of identified dimensions and areas for sustainable indicators (SIs) for outdoor light-emitting diode (LED) lighting and solid state lighting (SSL) [12].

3. Materials and Methods

The municipalities were randomly chosen from an official list of Swedish municipalities and based on the number of inhabitants in September and October 2019 [22]. A previous study analyzing the barriers and incentives for more energy efficient lighting in 12 Swedish municipalities revealed that they differed considerably in how they organized responsibilities and decision-making and how they worked strategically with strategic energy issues [23,24]. For example, smaller municipalities (ca. 10,000 inhabitants) seemed to work more efficiently with energy savings compared with medium sized (ca. 30,000–40,000 inhabitants) and larger municipalities (ca. 110,000–140,000 inhabitants). In

this study, it was therefore considered important to include municipalities of varying sizes. Sixteen municipalities seemed to be an appropriate number since 12 municipalities were considered enough to give a nuanced and complete picture of how municipalities work with energy-efficient lighting in their decision-making in the previous study.

The municipalities were divided into four classes by the number of inhabitants (class 1: 0–9999 persons, class 2: 10,000–19,999 persons, class 3: 20,000–49,999 persons, and class 4: >50,000 persons); see Table 1. In total, 16 municipalities were included in the analysis, four municipalities from each class. For a full list of names of the municipalities included, see Table A1. For some municipalities that were selected by the random number generator, it was subsequently not possible to locate the lighting master plan (even after direct contact with the municipality), and they were therefore excluded from further analysis. Lighting master plans were located by searching on the internet for words that could be used for lighting master plans, such as "lighting programs", "lighting plans", and "light plans" (in Swedish). In this study, the term "lighting master plan" is used synonymously with lighting plans or programs.

Table 1. Average number of inhabitants in the municipalities and the number of pages in municipal lighting programs for each class.

Class	Number of Municipalities	Range of Number of Inhabitants	Mean (Number of Inhabitants)	Standard Deviation (Number of Inhabitants)	Mean (Pages in the Lighting Program)	Standard Deviation (Number of Pages)
1	4	0–9999	7134	3155	14	18
2	4	10,000–19,999	16,666	2507	25	15
3	4	20,000-49,999	34,035	10,761	34	20
4	4	>50,000	77,062	11,718	70	83

The 16 municipal lighting master plans were analyzed in two separate processes and can be viewed in Figure 2. First, to answer the research questions on which SIs are used and not used, screening and matching analyses were conducted. The lighting master plans were studied in detail and screened for matches of indicators used in the original framework of sustainability indicators. The matching process consisted of free-text searches for identification of SIs mentioned in the municipal lighting master plans.

Second, to further develop the framework of sustainability indicators, the municipal lighting master plans were screened for identification of new indicators. The criteria for identifying sustainability indicators for outdoor lighting are described in greater detail in the initial performance evaluation framework of the sustainability framework and were based on input, output, consumption, impact, and reduction [12]. Each page of the lighting master plan was thoroughly read to identify possible indicators. The validation procedure was used to evaluate that the indicator was quantifiable and had a cause-effect relationship with lighting (that was considered relevant for sustainable development), and finally, it was estimated whether the indicator could be used in, for example, municipal lighting master plans or in projects. Indicators that did not fulfil these criteria were not used. Indicators passing the validation procedure were then used for a second screening of the municipal lighting master plans to identify whether they were used by other municipalities but had been missed in the first screening. The second screening was also used to ensure that no new indicators had been missed during the first screening analysis. The new indicators also needed to be placed within the suitable dimensions (ecology and environment, economy, social, and society) and areas within dimensions. In some cases, the indicators could be used in several areas. Occasionally, the addition of new indicators required an adaptation of the already established SIs. New SIs were also identified from the scientific literature. The literature in the area of sustainable development was reviewed within the project when analyzing the interactions between SIs and energy performance [13], and additional literature searches were also performed as snowball searches of publications and authors

(forwards). These searches were based on the literature review that was conducted to establish the original framework of SIs [12].



Figure 2. The analytical procedure of processes 1 and 2. MLM = municipal lighting master plans. Yellow = material and data used in the procedure. Green = results.

4. Results

4.1. Comparison of SIs in Municipal Lighting Master Plans and the Original Framework of SIs

Screening and matching between indicators in the original framework of SIs [12] and indicators used in the 16 municipal lighting master plans revealed that indicators were used across all classes of municipalities and are shown in Table 2. For the dimension of ecology and environment, 11 different SIs were used, varying between four to six indicators for each municipality class. Indicators representing LCA and energy efficiency were found in all classes of municipalities. Two of the six possible economic indicators from the framework were used but only by municipalities in classes 2 and 3. Five indicators (of the 24 in the framework) in the social and society dimension were found to be used in municipal lighting master plans. Human health indicators were only used by one municipality. The smallest municipalities (class 1) use indicators for ecology, LCA, economy, and social wellbeing, whereas the largest municipalities (class 4) use indicators for energy efficiency, traffic safety, and LCA.

Dimension	A roa	No. of Used Sta	Number of Matched SIs Per Class				
Dimension	Alta	No. 01 Osed 315	Class 1	Class 2	Class 3	Class 4	
	Ecology	3	2	1	1	0	
F 1 1	Light pollution	1	0	0	1	0	
Ecology and	ĹĊĂ	5	2	1	3	2	
Environment	Energy efficiency	2	1	2	2	1	
	Total	11	5	4	6	4	
Economy	Economy	2	0	2	2	0	
Economy	Total	2	0	2	2	0	
	Traffic safety	3	0	2	2	2	
Social and Society	Human health	0	0	0	0	0	
	Social wellbeing, quality of life, and equity	1	1	0	0	0	
	Total	4	1	2	2	2	

Table 2. Number of SIs used from the original framework divided into classes of municipalities.

The relative use of SIs in the municipal lighting master plans compared with the total number of indicators in the framework can be viewed in Table 3 and shows that all sustainability areas are included except for human health. However, the relative use differs greatly between the various areas. In the dimension of ecology and environment, the relative use differs between 6.3% for light pollution and 45.5% for LCA. For ecological impact, energy efficiency, light pollution and social wellbeing, quality of life, and equity, only 20% or less of the indicators were found to be used in the municipal lighting master plans; 33.3% of the economic indicators in the framework of SIs were used in municipal lighting master plans. In the social and society dimension, 21.4% of the indicators for traffic safety were used.

Table 3. Number of used SIs from the original framework, total numbers of SIs in the framework [12], and the relative use of SIs from the original framework in the municipal lighting master plans for 16 Swedish municipalities.

Dimension	Area	No. of SIs Used	Tot No. SIs	% Used
	Ecology	3	15	20
	Light pollution	1	16	6.3
Ecology and Environment	ĹĊĂ	5	11	45.5
	Energy efficiency	2	12	16.7
	Total	11	54	20.4
Economy	Economy	2	6	33.3
Economy	Total	2	6	33.3
	Traffic safety	3	14	21.4
Cosial and Cosiater	Human health	0	3	0
Social and Society	Social wellbeing, quality of life, and equity	1	7	14.3
	Total	4	24	12.5

A full list of the indicators used in the municipal lighting master plans can be found in Tables A2–A9.

4.2. New Sustainability Indicators

In total, 28 new sustainability indicators were identified, of which ten were placed in the dimension of ecology and environment and 18 were placed in the social and society dimension of sustainability; see Table 4. The indicators in the ecology and environmental dimension belonged to different areas, while the indicators in the social and society dimension were placed in traffic safety (4) and in social wellbeing, quality of life, and equity (14). No new indicators were identified in economy or human health. Most of the new indicators were identified from the municipal lighting master plans, 20 of 28, while eight originated from the literature (for further details, see Section 4.2.2 below).

Table 4. Number of	new indicators	per dimension an	d area and origin.
		1	0

Dimension	Area	No.	Lighting Master Plans	Literature
	Ecological impact	3	3	0
Ecology and Environment	Light pollution	4	2	2
LCA 2	2	0		
	Energy efficiency	1	1	0
	Economy	0	0	0
	Traffic safety	4	4	0
Social and Society	Human health	0	0	0
	Social wellbeing, quality of life, and equity	14	8	6
	Total	28	20	8

4.2.1. New Indicators in Ecology and Environment

In the area of ecology, three new indictors were identified in the municipal lighting master plans and can be viewed in Table 5. One of the class 3 municipalities states, "Trees and bushes should be cut in a way so that lighting is kept free from lichen, branches and garbage. In some cases, consideration needs to be taken to species protection regulation as protected groups of insects or other animals should not be affected negatively because trees are lit."

The same municipality further writes, "Excessive lighting is not only affecting humans negatively but also flora and fauna. Birds, bats, reptiles, insects, fishes and plants react to artificial light and are disturbed in their circadian and annual cycle. It disturbs especially nocturnal animals but can even get plants to bloom too early or birds to migrate at the wrong time. Therefore, it is important not to light nature areas or places where it is known that animals breed or live."

This was added as the following aspects:

- Consideration of the ecological impact
- No lighting in nature reserves in habitats
- No lighting in breeding habitats

The resulting new joint sustainability indicator was "implementation of local regulation", which can be implemented (yes/no) for each of the aspects.

In the area of light pollution, four new indicators were identified for regulations in light pollution in the following (see Table 5):

- For light distribution and obtrusive light, the European Standard "Light and lighting-Lighting of work places—Part 2: Outdoor work places", EN 12464-2 [25], includes limits for the upward light ratio (ULR) according to environmental zone, which should be implemented for outdoor working zones. ULR is defined as the "proportion of the flux of a luminaire or installation that is emitted, at and above the horizontal, when the luminaire(s) is (are) mounted in its (their) installed position" [3]. In EN 12464-2, the maximum obtrusive light permitted for exterior lighting installations is limited by the upward light ratio to 0–25% depending on the environmental zone (E1–E4). The new indicator reflects whether EN 12464-2 and the limits for ULR are implemented. The indicator could also be added to social sustainability since it concerns working environments.
- To reduce the impact on light pollution and the ecological impact of artificial light at night, it is recommended to sharply limit any blue spectral content of luminaires (see, e.g., [26]) and to adapt the use of light sources to correlated color temperatures (CCTs) below 3000 Kelvin (K) (e.g., [27,28]) and to a minimal amount of blue light (<500 nm), which can be applied or not. Several countries worldwide have already restricted the use of public and private outdoor lighting for light sources with high CCT. For example, the French ordinance concerning the prevention, reduction, and limitation of light pollution allows a maximum of 3000 K for outdoor lighting intended to facilitate safe travel, and public and private outdoor lighting related to economic activity. However, the use of CCTs to describe the spectral power distribution of light sources is suboptimal and the amount of blue light should be quantified by a more appropriate metric unit, which has not yet been established in standards or guidelines [13].
- Several municipalities mention that they use dimming schedules or adaptive/intelligent lighting systems. The strategic use of adaptive lighting can be quantified by a general implementation or in detail for specific areas and can also be measured as a percentage of the installations that have a schedule or system for this purpose.
- To reduce light pollution, flat lenses can be used and are common in municipal lighting master plans. For example, "Flat lenses make luminaires less luminant from the distance and direct the light downwards and less to the sides." Flat lenses are mentioned by two municipalities each in classes 2, 3, and 4, which shows an awareness

of these lenses. The indicator can be either the implementation of flat lenses or the proportions of lighting installations that have flat lenses.

In LCA, two new indicators were identified. Environmental certifications were mentioned by one municipality in class 2, and the lighting plan states: "Products should be produced according to an environmental certification system for example ISO 14000, EMAS, RoHS and/or REACH- directive." The eco-design directive is also mentioned. Environmental certification will increase the requirements of material usage, and the indicator should reflect whether a municipality uses certifications in the procurement processes.

Six different municipal lighting master plans in classes 2, 3, and 4 mentioned lighting poles and surface treatment. One of them states, "Poles for street lighting are usually galvanized and standard type for mounting in pre-fabricated foundations. The poles should have reinforced corrosion protection on the base." Improved materials for lighting poles should use better materials and should increase the lifespan of the products, thereby saving resources. The improvement of surface treatments of poles can be stated as a requirement, and the number of poles that have improved surface treatments can also be quantified as a percentage of the total number of poles.

Table 5. Variables, aspects, and suggested sustainability indicators (SIs) or measure for the new indicators in the environmental and ecology dimension. * New indicators from municipal lighting master plans. ** New indicators from the literature.

Variable	Aspect	Suggested SI		
Ecological impact				
Local regulations *	Show consideration of the ecological impact *	Implementation of local regulation * (Yes/no)		
Limit the extent of illuminated areas *	No lighting in nature reserve in habitats *	Implementation of local regulation * (Yes/no)		
Limit the extent of illuminated areas *	No lighting in breeding habitats *	Implementation of local regulation * (Yes/no)		
Light pollution				
	Light distribution **	EN12464-2-limit for ULR according to environmental zone **		
	Correlated color temperature (CCT) **	<3000 K (yes/no) **		
Regulations for light pollution	Dimming schedule adaptive/intelligent lighting systems * Reduce light trespass and pollution by flat lenses *	Implement (yes/no) or percentage of the lighting * Implement (yes/no) or percentage of the lighting *		
LCA				
Environmental certifications *	Increase the requirements of material usage *	Require environmental certifications (yes/no) *		
Materials for lighting poles *	Better materials will increase lifespan and save resources *	Require surface treatments* (yes/no) or percentage of the lighting *		
Energy efficiency				
Reduced energy consumption by controlled dimming	Dimming schedule adaptive/intelligent lighting systems *	Implement (yes/no) or percentage of the lighting *		

In the area of energy efficiency, one of the analyzed municipal lighting master plans states that the municipality should have a flexible, programmable control system for lighting. This system has "cycles for ignition, dimming and an alarm for error". Another municipality states that "new LED-luminaires with built-in dimming function that lower the light level by approximately 50% during low traffic should be used." The use of the indicator dimming can therefore be suggested, and adaptive systems can be a complimen-

tary aspect in saving energy with a reduced risk of affecting traffic safety (in the social and society dimension). For energy efficiency, an indicator is added regarding whether a dimming schedule or adaptive system is used (yes/no) or the percentage of lighting with one installed, similar to that for the indicator of light pollution.

For information on the classification of the different new indicators identified, see Tables A2–A9.

4.2.2. New Indicators in the Social and Society Dimension

Four new indicators were identified within the area of traffic safety from the municipal lighting master plans; see Table 6.

- Many master plans stated that, for road and street lighting, the standard national requirements and guidelines from the Swedish Transport Administration were used or referred to in the text for further information. The new indicator for traffic safety is therefore whether guidelines or standards are implemented (yes/no).
- As mentioned above, the possibility of using a dimming schedule or adaptive, intelligent lighting systems to save energy with no traffic safety impact can be implemented (yes/no) or indicated as a percentage of the installations. In this case, however, special consideration for traffic safety conditions must be clearly shown.
- A decrease in the glare of the outdoor lighting using flat lenses can be considered an indicator for traffic safety since it will improve traffic safety and visibility. Implementation of the usage of flat lenses for this purpose can be quantified by yes/no or by a percentage.
- The use of energy-absorbing lighting poles can improve traffic safety and is a new indicator in this area. This is mentioned by only one municipality without further explanation. Recommendations for the use of energy-absorbing poles should be implemented (yes/no), and it can also be measured as a percentage of the total number of lighting poles in an area.

Many new indicators were identified within the area of social wellbeing, quality of life, and equity; see Table 6.

- Municipalities of all four classes included the lighting of culture-historic buildings in their master plans. They state that "lighting of cultural environments may not result in a decrease of its culture-historic value." and "lighting of culture-historical buildings and environments can contribute to making them attractive and visible." The lighting in those areas "should be designed in a careful and considerate way" to show its character in the best way possible. This can be included as whether there are any guidelines for culture-historical buildings (yes/no). In this context, it is important to be aware that lighting for historical buildings such as churches may cause an unwanted negative impact on protected species such as bats and that lighting on buildings may contribute to sky glow.
- A class 3 municipality described that they have a control system installed. "Indications of system errors can be obtained through the electricity network, but the system is lacking communication from individual luminaires." The system lacks individual communication, but it is specified that such a kind of control system is available. Control systems of this kind can increase social wellbeing since errors can be detected more rapidly and are included with a yes/no indicator, whether it is used or not.
- In several municipalities, glare is brought up as an aspect in lighting programs, for example, "To prevent glare from coming up luminaires should be well- cut-off." All of them state that lighting sources should be fitted in such a way that glare is avoided without compromising human safety. There are several aspects within this variable as glare can be reduced by anti-glare optics or shielding, for example, by full cutoff, cutoff, and semi cutoff designs (see the cutoff classifications as defined by the Illuminating Engineering Society of North America (IESNA) [29]) or by using flat lenses, as mentioned above. Another aspect mentioned in one municipality lighting

master plan is that the lighting pole height next to buildings should be under the eaves to prevent glare for residents. In total, there are three new indicators of glare, as seen in Table 6.

- Landmarks are important for orientation within a landscape. One municipality stated
 that landmarks "can be lit for other reasons than their culture- historical value-they
 can be important objectives on a street or mark an entrance to something". Another
 municipality emphasized that "it is also important that the lighting of a landmark
 is balanced so that the surrounding environment is not experienced as too dark." It
 is important that landmarks are illuminated to ensure that it is possible to identify
 buildings and objects during dark hours. Landmarks are included as a new indicator
 and can be quantified by whether there are guidelines for the lighting design of
 landmarks.
- Filters should be included as an indicator in social wellbeing and quality of life, as they can affect environmental perception and social sustainability in areas where they are used. One municipalities state "There are plenty types of lighting filters which can be used to create effects, atmospheres and identity through lighting. The type of filter should be chosen according to the specific project or event." For example, playgrounds can be lit with filters to encourage children's active play. The presence of guidelines or the total number of areas with such filters can be used as indicators.
- Reassurance is defined as "the confidence a pedestrian might gain from road lighting when deciding to walk after dark" [30]. It is an important variable in sustainable outdoor lighting as people are more likely to walk when feeling safe. In the CIE 236 report "Lighting for pedestrians: a summary of empirical data" [10], uniformity and minimum horizontal illuminance instead of the mean are suggested as indicators for this variable. In Fotios et al. [30], a minimum horizontal illuminance of 2.0 lux is proposed together with uniform lighting, which are the main indicators affecting reassurance.
- Another important variable in social and society is pedestrian safety. This area can be divided into two aspects: obstacle detection and perceived safety. However, obstacle detection depends mostly on illuminance, and the scotopic/photopic ratio (S/P ratio) only makes a difference when the illuminance is low (0.2 lux) [1]. Therefore, the main indicators for the aspects of obstacle detection are illuminance (lux) and minimal horizontal illuminance, which should be between 1–2 lux [31]. Perceived safety, on the other hand, is more affected by the S/P ratio as whiter light (higher S/P ratio) sources increase the perceived safety of pedestrians [9]. According to Fotios and Yao [32], S/P ratio and CCT are correlated, and consequently, CCT and S/P ratio are included as indicators affecting the perceived safety of pedestrians.
- Remote disturbance is mentioned in a class 4 lighting master plan. Lighting can function as a disturbance when humans are exposed to it remotely, which is an unwanted effect. This variable affects social wellbeing, quality of life, and equity since it may have a negative impact on humans. Guidelines for the consideration of remote disturbances from lighting are included as an indicator.

For information on the municipality classification of the different new indicators identified, see Tables A2–A9.

Table 6. Variables, aspects, and suggested sustainability indicators (SI) or measures for the new indicators in the social and society dimension. * New indicators from municipal lighting master plans. ** New indicators from the literature.

Variable	Aspect	Suggested SI		
Traffic safety				
Road lighting design-traffic safety	Standard requirements for road lighting	Implement guidelines or standards (yes/no) *		
Dimming schedule adaptive/intelligent lighting systems	Save energy with no traffic safety impact	Implement (yes/no) or percentage of the lighting (with special consideration to traffic safety conditions)		
Glare	Decrease glare of outdoor lighting by use of flat lenses *	Implement (yes/no) or percentage of the lighting *		
Lighting poles *	Energy absorbing poles will increase traffic safety *	Implement (yes/no) or percentage of the lighting *		
Social wellbeing,	quality of life and equity			
Culture historical buildings *	Reduce/improve lighting *	Guidelines (yes/no) *		
Control system *	Notification of fixture failure *	Implement (yes/no) *		
	Reduce glare with anti-glare optics*	Implement (yes/no) or percentage of the lighting *		
Glare *	Reduce glare through shielding * Lighting pole height next to buildings under eaves *	Implement (yes/no) or percentage of the lighting * Guidelines (yes/no) or percentage of the lighting *		
Landmarks *	Identify buildings/objects through lighting *	Guidelines (yes/no) *		
Filter *	Create effects, moods and identity *	Guidelines (yes/no or total number of areas/playgrounds*		
Reassurance **	Pedestrians confident to walk after dark **	Uniformity **		
icussurarce	recontails connactified wark after dark	Minimum horizontal illuminance **		
	Obstacle detection **	Illuminance (lux) **		
	Obstacle detection	Minimal horizontal Illuminance 1-2 lux **		
Pedestrians safety **	Domosived extern	Correlated color temperature (CCT) **		
	rerceived safety	S/P ratio **		
Remote disturbance *	Remotely visible disturbances *	Guidelines (yes/no) *		

5. Discussion

This study shows that municipalities used established SIs in highly variable amounts in their lighting master plans. For more traditionally used areas, where there is a lot of previous knowledge and, in some instances, established tools available for use (e.g., life cycle cost (LCC) and LCA), the municipalities have adopted indicators that can be used for strategical decisions in the lighting planning process. Those SIs are also included in the framework, showing that tools established by authorities (e.g., LCC) or by international standards (e.g., EN 13201 or national road lighting standards) will receive more attention and will make an impact on municipal lighting planning.

In general, however, not many SIs are included and the aspects of relevance for sustainable development are not mentioned, for example, in the social sustainable dimension regarding human health and social wellbeing. Similarly, ecological and environmental aspects were rarely considered. However, this is not very surprising since there are few international or national guidelines or standards in these areas, and even when such exists, it will take a few years before they are implemented. The technical report CIE 234:2019 can be used to support procurement processes for local governments to increase the quality of lighting master plans. Furthermore, an increased awareness of scientific progress in the sustainable development of outdoor lighting may also help local governments improve the sustainability content of their lighting master plans.

However, it was possible to find information in the municipal lighting plans on example prioritized areas and aspects that should have indicators to improve the sustainable development of lighting planning and evaluations from a municipal perspective. Due to the lack of previous studies establishing causal-effect relationships, many of the new indicators are only quantified by whether they are included in the strategic work or if there are guidelines for their consideration. This study shows that there is a need for guidelines and recommendations for working with outdoor lighting from a sustainability perspective, especially in the social dimension, where most of the new indicators were identified. Apparently, there are no current guidelines for how municipalities should choose effective indicators for sustainable development, such as, key performance indicators. This makes it difficult for municipal officials, politicians, and municipal engineers to reach an agreement when making strategic decisions on outdoor lighting. Future work should aim to reduce the number of SIs. This can be done by interviewing experts and researchers on what priority to give the indicators, but it can also be done in an international project where researchers involve politicians and public officials to create a priority list of sustainability aspects. Apart from this, it is also important that the SIs can be used and that they are effective in planning, evaluations, and follow-up if the development of the outdoor lighting moves in a sustainable direction.

Municipal lighting master plans occasionally contain a lot of technical details, but why those details are recommended is usually not explained, and there are rarely references to other documents with more information or to standards or guidelines. One example is the use of CCT in municipal lighting plans. In most cases, the CCT of light sources is described in qualitative terms for humans and how humans experience lights of various colors, neglecting the fact that, in general, a higher CCT with more blue-rich light will save energy compared to lower CCT (see, for example, [33]). Also, artificial light, such as blue-rich LEDs, will have a negative impact on circadian rhythm across vertebrate taxa through melatonin suppression [34] and can cause negative ecological impacts and unwanted light pollution [26,28]. Planning sustainable outdoor lighting is a great challenge for society and should not be underestimated. Sustainable development of the outdoor lighting is based on a holistic approach. Consequently, applying single-sided approaches or approaches that consider as many aspects that a project group of various professional competencies can handle may still not be successful. For example, when planning road lighting in protected areas, recommendations of optimized lighting designs regarding light pollution, energy savings, and human visibility can be suggested [33]. However, if the ecological impact of the lighting is not identified and quantified properly, for example, by identification of light-sensitive species or by creating a priority list of species that should be protected via knowledge of how the species are impacted by artificial light at night, the suggested road lighting solutions will not be efficient or sustainable for areas designated for the conservation and protection of species.

Many municipal lighting master plans are very general and state fundamental facts. This was also observed in another study that analyzed lighting programs and plans in Sweden [35]. They also identified that there is a lack of guidelines for what should be included in lighting master plans, resulting in plans that have various levels of content and goals. This was also observed in this study since the number of pages in the municipal lighting master plans varied from two pages to 190 pages. It seems that the content of a lighting master plan may depend heavily upon the professional background of the person writing it and on the quality of the instructions for the work from the municipalities. Urban lighting designers, architectural lighting designers, and urban lighting planners are described as the "three musketeers" of urban lighting by K.M. Zielinska-Dabkowska [19]. Each profession possesses unique skills that are essential for delivering successful solutions for urban lighting. In Sweden, it is somewhat rare to employ an urban lighting planner; instead, consultants from various professions, educations, and experiences are often hired

as consultants to produce lighting master plans. This may contribute to the fact that lighting master plans are highly inefficient in including sustainability aspects. In fact, it can be questioned whether these are strategic planning documents since they will not fulfil, for example, the main objectives for a lighting master plan described in CIE 234 [20].

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Appendix A

Table A1. Classification of municipalities by the number of inhabitants, the number of pages, and the source for the municipalities' lighting master plans.

Municipality	Number of Inhabitants 2018	Class (1-4)	Pages in Lighting Master Plan	Source
Arjeplog	2794	1	41	Arjeplog 2014. Lighting Master Plan. 23 February 2015. Available at https://www.arjeplog.se/download/18.6 2e2b04814d439a87472323f/1431413766887/2 + Belysningsprogram.pdf (accessed online 5 May 2019).
Vansbro	6807	1	4	Vansbro 2013. Guidelines for exterior lighting. 5 November 2013. Available at https://vansbro.se/download/18.c71f29816bc1576d3 12dd5f/1563448360213/Gatubelysning%20i%20 Vansbro%20kommun,%20Riktlinjer.pdf (accessed online 18 June 2019).
Mellerud	9354	1	2	Mellerud 2019. Lighting policy. 26 June 2019. Available at https://www.mellerud.se/media/438550 /gatubelysningspolicy-2019-06-26.pdf (accessed online 19 August 2019).
Uppvidinge	9581	1	7	Uppvidinge 2018. Guidelines for exterior lighting. 16 October 2018. Available at https://uppvidinge.se/ download/18.1d469c2d16662db3e436db63/15434023 75518/Riktlinjer%20f%C3%B6r%20offentlig%20 belysning%20i%20Uppvidinge%20kommun.pdf (accessed online 21 August 2019).
Öckerö	12,945	2	28	Öckerö 2017. Zoning plan. 2 October 2017. Available at https://www.ockero.se/download/18.16430ecc16382 88b7ac8bb7c/1527848568280/%C3%96KP%20del%20 av%20Heden%201_300%20-%20Planbeskrivning.pdf (accessed online 20 June 2019).
Gällivare	17,630	2	13	Gällivare 2013. Lighting Master Plan. 2013 (no date). Available at http://www.gellivare.se/Global/Kommun%20och% 20Samh%C3%A4lle/Trafik%20och%20v%C3%A4gar/ SoT_2013_149%20-%20Handlingsplan%20belysning% 7BFCFE-625B-0000-975B-0000-A103%7D.pdf (accessed online 20 June 2019).
Eksjö	17,664	2	44	Eksjö 2014. Lighting Master Plan. 28 August 2014. Available at https://www.eksjo.se/download/18.1d2 a7c7616342fe18ec89651/1526974272982/Eksj%C3%B6 %20belysningsguide.pdf (accessed online 5 June 2019).

Municipality	Number of Inhabitants 2018	Class (1–4)	Pages in Lighting Master Plan	Source
Kramfors	18,423	2	14	Kramfors 2016. Lighting Master Plan. 1 June 2016. Available at https: //www.kramfors.se/download/18.1a6923ca15805d5 2c5def856/1478189666862/Belysningsplan.docx (accessed online 20 August 2019).
Lomma	24,763	3	31	Lomma 2017. Lighting Master Plan. 11 November 2018. Available at https://lomma.se/download/18.6c8293d1 67287b2ce364845/1542959750623/TN%202018-11-22 %20bilaga%20%C2%A7%2068.pdf (accessed online 5 June 2019).
Höganäs	26,566	3	35	Höganäs 2009. Lighting Master Plan. 20 January 2009. Available at https://www.hoganas.se/globalassets/documents/ invanare/bygga-bo-och-miljo/planavdelningen/ ovriga/ljussattningsprogram_2009-01-20.pdf (accessed online 5 June 2019).
Västervik	36,680	3	60	Västervik 2017. Lighting Master Plan. 27 March 2017. Available at https://www.vastervik.se/globalassets/ kommun-och-politik/forfattningssamling/ belysningsprogram-ks170327.pdf (accessed online 5 June 2019).
Sigtuna	48,130	3	11	Sigtuna 2014. Lighting Master Plan. 1 September 2014. Available at https://www.sigtuna.se/Global/Bygga_ bo_trafik/Gator%20och%20trafik/Gatubelysning/ Belysningsprogram%202014.pdf (accessed online 5 June 2019).
Mölndal	68,152	4	60	Mölndal 2014. Lighting Master Plan. 14 October 2014. Available at https: //www.molndal.se/download/18.6e3c002d15923 dacbcd470c/1553600063055/Belysningsprogram.pdf (accessed online 5 June 2019).
Kalmar	68,510	4	190	Kalmar 2016. Lighting Master Plan. 14 December 2016. Available at https://www.kalmar.se/download/18.3 d99d73715c38c8a9e14b5b/1496847676472/07_kalmar_ belysningsprogram_unika_kalmar.pdf (accessed online 5 June 2019).
Järfälla	78,480	4	18	Järfälla 2017. Lighting Master Plan. 27 April 2017. Available at https://www.jarfalla.se/download/18.7ff037531627 b287004c8fa9/1560945858833/belysningsprogram.pdf (accessed online 5 June 2019).
Botkyrka	93,106	4	11	Botkyrka 2009. Lighting Master Plan. 2009 (no date) Available at https://www.botkyrka.se/download/18.4 a23abd9158495687c9ea144/1486981486117 /Botkyrka%20belysningsprogram.pdf (accessed online 5 June 2019).

Table A1. Cont.

Area: Eco	ological Impact						
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Prevent and limit new areas being lit	Stop increases in ecological impact and light pollution	Establish and improve legislation/ recommendations/guidelines	0	0	0	0	0
0		Shut off lights (%)	1	0	0	0	1
		Use lamp shielding (%)	0	0	0	0	0
Limit the extent of illuminated areas	Reduce the ecological impact of current lighting	Eliminate over-lighting (light loss factor (LLF), lamp lumen depreciation (LLD), or maintenance factor)	0	0	0	0	0
	1 0 0	Follow minimum values for safety (e.g., roads)	0	0	0	0	0
		Establish maximum levels for other kinds of lighting (e.g., 1 cd/m ²)	0	0	0	0	0
		Light pollution	0	0	0	0	0
	Reduce the ecological impact of current lighting at biologically critical times	Reduce lighting at critical times of biological activity (migration/breeding/foraging)	0	0	0	0	0
illumination		Dimming schedule	1	1	0	0	2
		Adaptive lighting with activation sensors	0	0	0	0	0
Limit/change the intensity of light	Reduce the ecological impact of artificial light on	Luminous flux or luminous intensity per square meter	0	0	0	0	0
flux/intensity)	many organisms	$(Lm/m^2; Lx/m^2; cd/m^2)$	0	0	0	0	0
Limit/change the		Optical filters for wavelengths < 480 nm	0	0	0	0	0
spectral wavelength distribution of artificial light sources		Radiant p-band flux to photopic flux ratio (P-band)	0	0	0	0	0
0		Melatonin suppression index (MSI)	0	0	0	0	0
Sensitive areas	Reduce/improve lighting	Improve and change lighting to reduce the impact in sensitive areas	0	0	1	0	1
Local regulations *	Show consideration of the ecological impact *	Implementation of local regulation (yes/no) *	0	0	1	0	1
Limit the extent of illuminated areas *	No lighting in nature reserve in habitats *	Implementation of local regulation (yes/no) *	0	0	1	0	1
Limit the extent of illuminated areas *	No lighting in breeding habitats *	Implementation of local regulation (yes/no) *	0	0	1	0	1

Table A2. All indicators in the area of ecological impact matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans.

Table A3. All indicators in the area of light pollution matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans. ** New indicators from the literature.

Area: Light Pollution							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Reduce (growth of) light pollution	Light pollution in an area –	Number of luminaires/area	0	0	0	0	0
		New luminaires in non-lit area	0	0	0	0	0
Reduce/recommend levels of outdoor lighting for non-roads	Light pollution management	National or regional guidelines on levels of lighting (see also regulations for light pollution)	0	0	0	0	0
Shielding of luminaires	Reduce light pollution and trespassing light from luminaires	Full cutoff, cutoff, semi cutoff, and sharp cutoff designs	0	0	0	0	0

Area: Light Pollution							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
		Optical filters for wavelengths < 480 nm	0	0	0	0	0
Reduce blue-rich light	Reduce light pollution by changing the spectrum of	Radiant p-band flux to photopic flux ratio (P-band)	0	0	0	0	0
(and UV)	new light sources	Melatonin suppression index (MSI)	0	0	0	0	0
		Star light index (SLI)	0	0	0	0	0
Reduce duration of illumination	Reduce light pollution by innovative design	Innovative technology (for example controllable by the public) and/or activation sensors	0	0	1	0	1
		Loss of star visibility	0	0	0	0	0
Sky glow and sky	Measure and monitor the light pollution effects	Number of visible stars	0	0	0	0	0
brightness		Visibility of the Milky Way	0	0	0	0	0
		Measuring with sky quality meters	0	0	0	0	0
	Reduce light pollution	Maximum levels of permissible illuminance or luminance for different lighting applications and their reflection	0	0	0	0	0
Regulations for light pollution	Light distribution **	EN12464-2-limit for ULR according to environmental zone **	-	-	-	-	-
	Correlated color temperature (CCT) **	3000 K (yes/no) **	-	-	-	-	-
	Dimming schedule adaptive/intelligent lighting systems *	Implement (yes/no) or percentage of the lighting *	0	1	1	0	2
	Reduce light trespass and pollution by flat lenses *	Implement (yes/no) or percentage of the lighting *	0	2	2	2	6
		Barriers to stop trespassing light	0	0	0	0	0
Barriers	Reduce light trespass and pollution	Specially designed lighting to avoid light trespass in adjacent areas	0	0	0	0	0

Table A3. Cont.

Table A4. All indicators in the area of LCA (life cycle assessment) matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans.

Area: LCA							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Luminous efficacy	Luminous flux and power (energy consumption)	Lumen/watt (Lm/W)	0	0	1	1	2
Life cycle	Longer operating life will save resources	Hours of operation during lifetime (h)	1	0	0	1	2
Enormy and CO	Energy consumption or	kWh (energy)	0	0	0	0	0
Energy and CO_2	CO_2 for the use phase	$kg CO_2 (CO_2)$	0	0	0	0	0
Energy production	Environmental impact will be reduced by use of renewable energy sources	kWh (energy)	0	0	0	0	0
	in the use phase	Solar or wind-powered lights	1	0	1	0	2
Raw and rare materials	Nonzonovahla zasovzesa in	Heat sink of aluminum	0	0	0	0	0
	the manufacturing process	(kg or kg-equivalent antimony (Sb)) extraction impact	0	0	0	0	0

Area: LCA							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Waste material	Impact, reuse, and recycling of components; includes aspects of hazardous waste and possibilities for recycling	kg (of waste product)	0	0	0	0	0
		Hazardous waste	0	0	1	0	1
		Recycling	0	1	0	0	1
Environmental certifications *	Increase the requirements of material usage *	Require environmental certifications (yes/no) *	0	1	0	0	1
Materials for lighting poles *	Better materials will increase lifespan and save resources *	Require surface treatments* (yes/no) or percentage of the lighting *	0	2	2	2	6

Table A4. Cont.

Table A5. All indicators in the area of energy efficiency matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans.

Area: E	nergy Efficiency						
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Energy efficiency	Energy efficiency based on energy and light per km	kW/Lx/km or kW/cd/m ² /km or	0	0	0	0	0
	road (per year)	kWh/lx/km or kWh/cd/m ²	0	0	0	0	0
Mesopic design or spectral	Maximize visual	Scotopic/photopic (S/P) ratio	0	0	0	0	0
distribution of the light source	performance and energy savings	Correlated color temperature, degrees Kelvin (K)	1	2	3	2	9
Light loss factor and lamp lumen depreciation	Minimize energy waste in the design and use stages	Light loss factor (LLF), lamp lumen depreciation (LLD), or maintenance factor	0	0	0	0	0
		Intelligent lighting to control LLF	0	0	0	0	0
	Energy savings in accordance with demand Dimming schedule or adaptive/intelligent lighting systems *	Yes/No	0	2	1	0	3
Reduced energy		Percentage savings (kWh/year)	0	0	0	0	0
consumption by controlled dimming		Implement (yes/no) or percentage of the lighting *	0	1	1	0	2
Diment and in diment	Due di ete di en enere e contin e e	Percentage (rebound effect)	0	0	0	0	0
robound offects	will be underestimated	Number of luminaires/area	0	0	0	0	0
rebound effects	will be underestimated	New luminaires in non-lit areas	0	0	0	0	0
Surface luminance	Energy savings through increased luminance by changing the surface characteristics or adapting light levels to changed surface conditions.	cd/m ² , luminance or road surface reflection coefficient (for measurement of brighter surfaces). Percentage savings (kWh/year) due to intelligent lighting compensation for surface characteristics	0	0	0	0	0

Table A6. All indicators in the area of economy matched with the lighting plans of the four classes of municipalities: no new indicators.

Area: Economy							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Life cycle costs	Economic comparison of lighting products	Life cycle cost analysis (LCC, monetary value)	0	1	1	0	2
Pay-back time	Return of investments	Payback time (PB) on return of investment	0	0	0	0	0
Economic	Economic health and growth correlated to lighting	Regional GDP per luminaire	0	0	0	0	0
sustainability		Regional GDP per luminous flux per area	0	0	0	0	0

Area: Economy							
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Dimming	Economic savings due to dimming schedules	Percentage energy savings per year PB	0	1	1	0	2
Cost benefits and external costs		Savings due to the reduced number of accidents when lighting is installed	0	0	0	0	0

Table A6. Cont.

Table A7. All indicators in the area of traffic safety matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans.

Are	ea: Traffic Safety						
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Traffic safety	Traffic safety monitoring	Number of traffic accidents	0	0	0	0	0
		Luminance (average cd/m ²)	0	0	0	0	0
		Luminance uniformity (minimum luminance/average luminance)	0	0	0	0	0
Road lighting		Illuminance (average lux)	0	0	0	0	0
design traffic safety	road lighting	Illuminance uniformity (minimum illuminance/average illuminance)	0	0	0	0	0
		Implement guidelines or standards (yes/no) *	1	3	2	4	10
		Scotopic/photopic (S/P) ratio	0	0	0	0	0
	New standard for road lighting	S/P ratio	0	0	0	0	0
Mesopic design		Correlated color temperature (K)	0	2	3	3	9
Dimming	Save energy with no traffic safety impact	Percentage of full wattage per hour (or of saved energy per year)	0	1	1	0	2
tive/intelligent lighting systems		Implement (yes/no) or percentage of the lighting (with special consideration to traffic safety conditions) *	0	1	0	0	1
		Glare index (GR)	0	0	0	0	0
		Threshold increment (TI)	0	0	0	0	0
Glare	Estimation of glare	Veiling luminance	0	0	0	0	0
		Shielding (full cutoff, cutoff, semi cutoff, and sharp cutoff designs)	0	0	0	1	1
Glare	Reduce risk of outdoor lighting glare	Reduce glare from non-road lighting	0	0	0	0	0
Glare	Decrease glare of outdoor lighting by use of flat lenses *	Implement (yes/no) or percentage of the lighting *	0	2	2	2	6
Lighting poles *	Energy absorbing poles will increase traffic safety *	Implement (yes/no) or percentage of the lighting *	0	2	2	2	6

Table A8. All indicators in the area of health impact matched with the lighting plans of the four classes of municipalities: no new indicators.

Area:	Health Impact						
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Blue and UV light hazard	Photobiological hazard	-	0	0	0	0	0
Flicker	May cause health effects	-	0	0	0	0	0
	Impact on circadian rhythm	Melatonin suppression index (MSI)	0	0	0	0	0
Non-visual effects of light		Luminous flux/area (lm/area)	0	0	0	0	0
		Questionnaire	0	0	0	0	0

Table A9. All indicators in the area of social wellbeing, quality of life, and equity matched with the lighting plans of the four classes of municipalities. Grey areas = new indicators. * New indicators from municipal lighting master plans. ** New indicators from the literature.

Area: Social Well	lbeing, Quality of Life and Equity						
Variable	Aspect	Suggested SI or Measure	Class 1	Class 2	Class 3	Class 4	Total
Criminality	Crimes	Number of crimes in an area	0	0	0	0	0
		POLQ questionnaire	0	0	0	0	0
Environmental perception	Perceived outdoor lighting quality	Illuminance (lux)	1	0	0	0	1
rtr	4	Scotopic/photopic (S/P) ratio	0	0	0	0	0
Light pollution	Aspects of light pollution and discomfort glare	De Boer scale rating survey	0	0	0	0	0
		POLQ questionnaire	0	0	0	0	0
Equity	Increase equity	Investments in old lighting systems irrespective of location	0	0	0	0	0
Culture historical buildings *	Reduce/improve lighting *	Guidelines (yes/no) *	0	0	0	0	0
Control system *	Notification of fixture failure *	Implement (yes/no) *	0	0	1	0	1
	Reduce glare with anti-glare optics *	Implement (yes/no) or percentage of the lighting *	0	0	0	0	0
Glare *	Reduce glare through shielding *	Implement (yes/no) or percentage of the lighting *	1	0	2	0	3
	Lighting pole height next to buildings under eaves *	Guidelines (yes/no) or percentage of the lighting *					
Landmarks *	Identify buildings/objects through lighting *	Guidelines (yes/no) *	1	0	1	2	4
Filter *	Create effects, moods and identity *	Guidelines (yes/no or total number of areas/playgrounds *	0	0	1	0	1
Deservement as **	Pedestrians confident to	Uniformity **	-	-	-	-	-
Reassurance	walk after dark **	Minimum horizontal illuminance **	-	-	-	-	-
		Illuminance (lux) **	-	-	-	-	-
Pedestrians	Obstacle detection **	Minimal horizontal illuminance 1–2 lux **	-	-	-	-	-
salety	Democional estates	CCT (Correlated color temperature) **	-	-	-	-	-
	Perceived safety	S/P ratio **	-	-	-	-	-
Remote disturbance *	Remotely visible disturbances *	Guidelines (yes/no) *	0	0	0	1	1

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