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Article

New Framework of Sustainable Indicators for Outdoor LED (Light Emitting Diodes) Lighting and SSL (Solid State Lighting)

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Abstract: Light emitting diodes (LEDs) and SSL (solid state lighting) are relatively new light sources, but are already widely applied for outdoor lighting. Despite this, there is little available information allowing planners and designers to evaluate and weigh different sustainability aspects of LED/SSL lighting when making decisions. Based on a literature review, this paper proposes a framework of sustainability indicators and/or measures that can be used for a general evaluation or to highlight certain objectives or aspects of special interest when choosing LED/SSL lighting. LED/SSL lighting is reviewed from a conventional sustainable development perspective, *i.e.*, covering the three dimensions, including ecological, economic and social sustainability. The new framework of sustainable indicators allow prioritization when choosing LED/SSL products and can thereby help ensure that short-term decisions on LED/SSL lighting systems are in line with long-term sustainability goals established in society. The new framework can also be a beneficial tool for planners, decision-makers, developers and lighting designers, or for consumers wishing to use LED/SSL lighting in a sustainable manner. Moreover, since some aspects of LED/SSL lighting have not yet been thoroughly studied or developed, some possible future indicators are suggested.

Keywords: sustainable development; exterior; ecological; environmental; economic; impact; light pollution; safety; visibility; social

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1. Introduction

About 19% of total global electricity production is used for artificial lighting, causing about 1900 Mt of CO_2 emissions per year [1]. Energy consumption by outdoor lighting is often high owing to the long operating hours and high wattage necessary for traffic visibility and public safety. For example, street lighting may account for 60% of total electricity consumption by a municipality [2]. Inevitably, maintaining public lighting often constitutes a substantial proportion of municipal budgets [3]. Road lighting installations usually have a long life, sometimes spanning 30–40 years and it is therefore common to have inefficient and expensive street lighting systems [3,4]. Such lighting systems will need to be replaced in the forthcoming future, preferably with a long-term sustainable and cost-efficient outdoor lighting system.

The solid state lighting (SSL) technology is evolving rapidly and can offer energy-efficient, long-lasting and environmentally friendly products such as, for example, light emitting diode (LED) lamps [5]. Due to the large energy savings with LED lighting, a switch from e.g., mercury vapor, high pressure sodium (HPS) or ceramic metal halide light sources can translate into cost savings and lower CO_2 emissions in forthcoming decades for lighting installation owners, e.g., [5–7]. Since LED lighting is also very suitable for energy-saving schemes, it is possible to be used for adaptable and intelligent street and road lighting systems, thereby further reducing energy consumption, for example [8].

Considering LED/SSL installations from a strict energy and CO_2 emissions perspective, there appear to be no disadvantages to replacing old equipment. However, from a sustainable development perspective other important aspects of LED/SSL lighting arise and these are not entirely advantageous. For example, while the energy savings may be large, the use of LED lighting can increase light pollution [9,10], ecological impacts [11], and environmental degradation [12]. Old lighting technology, such as low pressure sodium (LPS) and HPS lighting, is claimed to be more beneficial from an astronomical and environmental perspective [9,13], but cannot be dimmed and has a very low scotopic/photopic (S/P) ratio [14], indicating lower visibility. SSL lighting technology options are generally more energy efficient, can be dimmed and thus reduce lighting levels and have a higher S/P ratio and color rendering index, e.g., [15]. Since LED lighting in outdoor installations is a rather recent phenomenon, there are also several important aspects of its use that have not yet been thoroughly examined, such as unwanted effects of glare and potential rebound effects of cheaper lighting. Nevertheless, street lighting is one of the fastest growing applications of LED technology [5].

It is important to fully evaluate and prioritize all the different aspects and impacts of LED/SSL lighting when planning ahead for a sustainable and long-term lighting system in outdoor applications. Currently, however, while choosing LED lighting from a strictly energy or economic perspective is a straightforward decision, it is much more complicated to choose appropriate products for different aspects of sustainability. For example, if wanting to reduce overall environmental impact or to enhance social sustainability, there are few guidelines available. There is currently no sustainability indicator-based system to be used for evaluations of LED/SSL lighting systems, and the existing transport indicator systems [16,17] and the European transport and environmental indicator systems [18] are difficult to apply and not relevant for application to lighting systems *per se*. It is therefore extremely difficult for lighting planners or designers to choose an optimal LED/SSL product when wanting to evaluate and consider other aspects besides energy, CO_2 emissions or costs. Bearing in mind the long time perspective of outdoor lighting systems, it is especially worrying if aspects of sustainability such as the environmental or social impact are neglected due to lack of information when replacing old lighting systems.

The aim of the paper is to propose a new framework of sustainability indicators (SI) or in some cases, measures, that can be used for a general evaluation or to highlight certain objectives or aspects of special interest when choosing LED/SSL lighting systems. LED/SSL lighting is therefore investigated by a literature review from a conventional sustainable development perspective, *i.e.*, including the three dimensions ecological, economic and social sustainability. The proposed framework of sustainable indicators are intended to permit prioritization when choosing LED/SSL products and thereby help ensure that short-term decisions on LED lighting systems are in line with long-term sustainability goals established in society. The new framework will hopefully advance the sustainable development and research area of outdoor lighting substantially because currently, there is no such system available. The framework is also intended to act as a tool for planners, decision-makers, developers, lighting designers or consumers seeking to use LED/SSL lighting outdoor in a sustainable manner. In addition, since various aspects of LED/SSL lighting have not been thoroughly studied or developed as yet, various types of further research needed in order to gain a full and comprehensive understanding of all sustainability aspects of LED/SSL lighting are briefly discussed, for example, ecological impact, external costs and social sustainability.

2. Sustainability

Sustainability as a concept can be divided into three fundamental perspectives: the normative, the scientific and the strategic [17]. In this study, the normative perspective is taken to represent the dimensions and key principles of sustainable development and is defined in this chapter. The scientific perspective defines the process and methods for identifying sustainability indicators and is used when choosing and suggesting indicators in this paper, while the strategic perspective of planning and decision making is applied to the results of the analysis.

The normative perspective includes the widely accepted definition of sustainable development established by the Brundtland report: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [19]. Furthermore, sustainable development is considered to be a process rather than an end state, for example in supporting change in decisions, direction of investments and reorientation of technological development. The Rio summit meeting of the UN in 1992 (UN Conference on Environment and Development in Rio de Janeiro, Brazil) established the idea that sustainable development has three dimensions/pillars that need to be considered simultaneously (ecological, economic and social dimensions) and mentioned the need for a fourth pillar, the institutional dimension. These dimensions may overlap and there may be interdependencies between them.

Sustainable development within transportation can be compared to sustainable development of street lighting, since many outdoor lighting systems are placed around road infrastructure. In sustainable development for transportation, the ecological dimension includes the impact of air pollution, climate change, noise and water pollution, habitat and biodiversity loss, hydrological impacts and depletion of non-renewable resources [20]. Examples of economic impacts include traffic congestion, infrastructure costs, consumer costs, mobility barriers, and accident damage. Examples of the social impact are associated with human well-being are equity, health, mobility barriers, aesthetics, community cohesion and livability [20].

However, while light pollution is considered a specific indicator of the environmental impact of transport systems [21], there are very few other relevant aspects of outdoor lighting included in the various sustainability indicators suggested for infrastructure or transportation.

3. Sustainability Indicators

Indicators are commonly used as a tool for policymaking and as decision support to ensure that various goals, objectives and targets can be measured, monitored and fulfilled. Indicators enable comparisons between systems or products and provide necessary information for decisions on future change towards sustainable development. Sustainability indicators are based on the ecological, economic and social dimensions of sustainability. According to Agenda 21, sustainability indicators need to "provide [a] solid basis for decision-making at all levels and contribute to a self-regulatory sustainability of integrated environment and development systems" [22].

An indicator must be a specific variable that arises from a value or measurement and is therefore based on a scientific concept and is suitable for quantification in a neutral manner in terms of a number or statistical analyses, e.g., [23]. In comparison, qualitative measurements are generally more difficult to use as indicators, since they are not as easily measurable and comparable.

While indicators may be based on scientific assumptions, the selection and use of indicators may instead reflect goals or targets decided by decision-makers, users or planners. Thus, it is important that the users of indicator systems understand the underlying assumptions, because the indicators chosen for assessments can influence the results [23].

Sustainability indicators are often chosen within a framework with specific goals and numerous indicators may be available. It is therefore common to aggregate and transform indicator values to a similar scale, e.g., between 0 and 1, and to use index values (*i.e.*, a group of indicators summarized to a single value). In some cases a normalized composite index is used to show the general trend for all dimensions of sustainability, but it is also possible to calculate a composite index separately for each dimension of sustainability.

When generating indicators, initial performance evaluation framework can be defined by different elements. In a study of transport sustainability, these could include input, output, consumption, impact and reduction [24]. The input is defined as any input of resources into the system, the output as the products produced by the system, consumption is services used, impact is negative effects caused by the system while reductions is defined as conservation of resources by decreased inputs or increased recycling [24]. In this paper, the main focus is on input, output, impact and reduction and on different aspects of the three dimensions of sustainability, as revealed by a literature search.

4. Methodology

A systematic literature review of outdoor lighting, focusing on sustainability aspects, was performed to obtain scientific research findings and results from the grey literature (often classified as research publications that have not been published as peer-reviewed papers or monographs by a publishing company, for example conference abstracts in reports published by organizations, institutions or administrative authorities). Literature was also sometimes found by the "snowball" effect, *i.e.*, through the reference list in papers of interest and through subsequent publications citing these papers. In addition, when sustainability dimensions and the possible impact of LEDs in outdoor lighting were initially mapped, discussions on relevant indicators took place with three officials from the Swedish Energy Agency working on energy efficiency and e.g., lighting standards. The Swedish Energy Agency also supplied information about grey literature for the review, e.g., on life cycle assessments (LCA) and reviews on the health effects of LED/SSL [25–27]. The number of databases used in each search depended on the amount of literature that was initially found and the searches were sometimes modified during the process, but are described in detail below. The literature searches included all languages available. There were no way to ensure that all relevant literature was found but in some cases sustainable development and LED/SSL lighting was also searched in Google or Google scholar to find additional literature and to make sure the relevant references had all been found.

4.1. Databases

The following databases were used in the literature search:

- TRID [28]
- Scopus [29]
- Web of Science [30]
- Swedish Transport Research Portal [31]

TRID is a bibliographic database with records from the Transportation Research Information Services (TRIS) database and the OECD's Joint Transport Research Centre's International Transport Research Documentation database (ITRD). TRID focuses on the transport sector and contains articles from scientific journals but also reports, dissertations, conference papers and proceedings, as well as sector magazines that are rarely included in Scopus or Web of Science. More than one million transportation research publications can be accessed via TRID. Scopus and Web of Science are bibliographic databases with the focus on scientific articles within a large range of disciplines and research areas. The Swedish Transport Research Portal is a national transport library catalogue that contains references to printed publications in the VTI (the Swedish National Road and Transport Research Institute) library and electronic publications within the areas of traffic, transport, transport infrastructure, vehicles, road users and the travelling public.

4.2. Literature Search Methodology

Search terms within defined areas were grouped and the groups were then combined with each other in different ways depending on the database, the number of hits and the meaning of the words. Various ending of words were included by using truncation, for example a search on "psychology *" yielded hits on both psychology and psychological, a search on "sustainab *" gave hits on both sustainability and sustainable, and "road *" produced hits on roads and roadways. Different variations of expressions, such as ecotunnel or eco tunnel, were also used.

The searches were executed in the fields of title, subject heading and abstract, depending on databases and hit volumes. When hit volumes were very large, *i.e.*, several thousand hits, the search was narrowed through searches in the title field or subject field. Different combinations of word groups were used, for example a search was performed on the main subject and the outdoor aspect in the title field. This yielded a reasonable amount of hits to go through without narrowing down the search by including a third group of search terms. A third group of search terms would have increased the precision of the search, but would also have reduced the coverage, since it might have overlooked relevant words and expressions used in the references. An information or literature search is always a trade-off between coverage and accuracy, especially when the main subject is LED, since there is much literature available within many areas.

The outdoor aspect had to be included in Scopus and Web of Science but was not needed in TRID, since the transport database did not include much literature on interior lighting. In TRID, therefore, all references to LED and light emitting diodes for the period 2010–2014 were sought. When searching for "artificial light" and "wildlife", this gave a search of good precision without the need to add further search terms, while searching for "illumination" and "animal" gave many hits of little interest and therefore needed to be narrowed down with search terms on e.g., "ecology" or "pollution", *etc.*

4.3. Literature Search Words and Groups

Six different searches (or information gathering) that partly overlapped in their research areas were performed. These were LED, artificial light, LCA (life cycle analysis), sustainability, CO_2, energy, social and economic sustainability, sustainability indicators, vehicle speed, traffic safety, energy efficiency, decision making and rebound effects.

4.3.1. LED

To investigate publications containing LED in the transport area, a search on all hits of LED and light-emitting diodes in combination with light/lamps was performed in September 2013 for the years 2004–2013 in TRID and for all years in the Swedish Transport Research Portal.

4.3.2. Artificial Light

The search on artificial light was performed in October 2014, in TRID from 2004 onwards, in Scopus from 2008 onwards and in Web of Science from 2010 onwards. The main search terms used were artificial light, illumination, light, lamp, luminance, sky glow. Ecological terms were biodiversity, biotope, eco tunnel, wildlife, ecology, habitat, ecosystem, environment, pollution, and fauna. The search was also performed on combinations such as animal/fauna/vegetation and bridge/tunnel/culvert/crossing. In Scopus and Web of Science, some searches included a third search term to add the outdoor aspect, for example: street, road, highway, outdoor or exterior. Searches were also conducted with different expressions such as nocturnal light, illuminated city, constant light and light pollution, together with different combinations of the main and ecological search terms. In Scopus, the search terms "lamp *" or "light *" or "lumen *" or "illum *" had to be included to reduce the amount of hits.

4.3.3. LCA, Sustainability, CO_2 and Energy

The search on these topics was performed in September 2013 from 1990 onwards in the three different databases. The main search terms used were high-pressure sodium, HPS, metal halide, MH, light-emitting diode, LED, electrode less fluorescent lamp, magnetic induction lamp, new generation light and next generation light. Sometimes the searches were performed on combinations with lighting, illumination, illuminance, light, lamp, and luminance. The second group of search terms was life cycle, LCA, carbon dioxide, CO_2, greenhouse, ecology, environment, pollution, emission, sustainability, ecosystem, sky glow and energy.

Searches were also performed on separate terms such as light pollution, constant light, continuous light, nocturnal light, sky glow and illuminated city. To cover the outdoor aspect (in Scopus and Web of Science), a third group of search terms was added and included road, highway, street, footway, sidewalk, side walk, pavement, walkway, outdoor, public, pedestrian, road light, street light and street lamp.

4.3.4. Social and Economic Sustainability

This search was performed in October 2014 from 2010 onwards in the three different databases (TRID, Scopus, and Web of Science). The main search terms were LED or light emitting diodes, while the second group of search terms reflected the outdoor aspect and included outdoor, exterior, road, highway, street, urban, town, city, rural, pavement. The third group of search terms was social, sociology, society, economic, cost, maintenance, life cycle, LCA, policy, politics, decision, criminal, crime, offence, psychology, cognition, implement, introduction, installation, energy, lux, luminance, comfort, attitude, perception, disturbing, residential, resident.

4.3.5. Sustainability Indicators

A search on "sustainability indicators" was performed in Scopus on 31 October 2014 and yielded 7023 hits. On adding "transport" as a search term, there were 810 hits. "Sustainability indicators" and "light emitting diode" gave no hits at all. "Sustainability indicators" combined with "light led" gave 14 hits, but no direct literature about effects or impacts of LED lighting outdoor applications.

4.3.6. Vehicle Speed, Traffic Safety, Energy Efficiency, Decision Making and Rebound Effects

For these various areas, previous research projects have been performed [3,32–35]. Furthermore, for traffic safety, road light and human factors, there are books dealing in detail with these issues [14,36,37].

A search on LED and vehicle speed was conducted in October 2013 and included hits from 2010 onwards in Scopus, TRID and the Swedish Transport Research Portal. The main search term was LED or light emitting diodes, while the second search term was speed and the traffic aspect was included as a third group of search terms by driver, driving, traffic, vehicle, car and automobile.

Another search for LED/light emitting diodes or lamps/road lights and pedestrians was performed in September 2013. This search was performed in TRID and the Swedish Transport Research Portal and included all years available.

In addition, a search of road lighting in combination with energy savings or accidents was performed in Scopus in November 2014.

5. Sustainability Indicators for LED/SSL Lighting

This chapter deals with the ecological, economic and social dimensions of sustainability. Each dimension is then further divided into subsections discussing sustainability areas and possible sustainability indicators in these areas.

5.1. Ecological (or Environmental) Sustainability of Outdoor Lighting

The main environmental areas of sustainability for outdoor lighting were found to be ecological impact, energy efficiency, light pollution and LCA results. Energy efficiency and LCA represent areas for input (energy and resources are used to build and maintain lighting systems), while output and impact are represented by ecological impact, light pollution and LCA (for example output in terms of waste). However, the areas are also intertwined, since e.g., applying technological advancements may significantly affect the other areas/indicators and light pollution causes/effects such as sky glow and ecology.

5.1.1. Ecological Impact

The ecological impact from light pollution was classified here in accordance with Longcore and Rich [38] as "artificial light that alters the natural patterns of light and dark in ecosystems" (*i.e.*, ecological light pollution). The ecological impact from artificial light comprises permanent installations and their trespassing light, but also mobile light pollution sources such as vehicle and traffic lights or other lights from transportation, as well as temporary light sources, for example decorative lighting. Not all light sources contribute to sky glow, but they may still have potential ecological impacts. Therefore, the discussion on light pollution (in Section 5.1.3) deals with non-ecological or astronomical aspects. However, light pollution is often used in the literature without this distinction and the effects are not easily separated. Therefore, sustainability indicators and aspects mentioned in this section are sometimes repeated in the light pollution section, but the focus in the two sections is a little different.

Studies on the ecological effects of light consist of comprehensive reviews of different aspects such as organism groups [39,40], behavior and population ecology, community ecology [38] and the mechanistic perspective [41]. There are also a vast number of species-specific research papers with different perspectives on artificial lighting. Moreover, reports, reviews and guidelines have been published in this area (for example [13,42,43]). However, very few ecological studies have been undertaken to date to investigate lighting effects of LED/SSL, but see [11,44].

Unfortunately, many ecological studies are lacking important lighting information, such as light source, power effect, spectral distribution, luminous flux, lamp post spacing and other important photometric basic data, so it is very difficult to draw any general conclusions based on the data [41]. Furthermore, many previously published papers investigate the effects of artificial light from lamps with light sources (e.g., mercury vapor lamps, HPS or LPS) that are currently not on sale or not in use, making the results impossible to implement for lighting planners and designers working solely with products available on the current market.

However, there is solid and strong evidence of a wide range of ecological impacts of artificial light pollution, for example on the movements, foraging, interspecific interactions, communication, reproduction and mortality of organisms [45]. There are also strong indications of far-reaching ecosystem impacts [46]. Despite this, the overall ecological impact of artificial light has been questioned, since effects on organisms and species differ significantly and strict scientific experiments investigating the effects of artificial lighting on organisms demand complicated designs and areas without light pollution as controls, making such research almost impossible to conduct. Therefore, it is not surprising that there are currently major research gaps in e.g., the impact on ecosystems, populations, landscape and evolution, but also concerning thresholds on the intensity/duration/extent/seasonal timing of lighting, as well as the spatial extent and how light pollution in terms of sky glow affects ecosystems/populations/species.

In order to overcome this dilemma, ecologists have started to focus on reducing the ecological consequences of artificial light pollution, arguing that effects do indeed exist but we know too little about them. Due to the current state of the research area, it is impossible to find general and readily implementable sustainability indicators to describe the ecological impact of artificial light. Artificial lighting generally does not seem to have any ecological benefits, especially not in natural environments, and should therefore be reduced as much as possible to minimize ecological impacts and damage.

The following measures or policy's have been proposed in the literature to reduce light pollution and its ecological impacts [9,45,47]: prevent and limit new areas being lit, limit the extent of illuminated areas by e.g., shut-off lighting, shielding, limiting the luminous intensity distribution, reducing trespassing light and eliminating overlighting and glare, limit the duration of light, limit/change the intensity of light (luminous flux), and limit/change the spectral wavelength distribution of light sources (see Table 1). Furthermore, by installing luminaires correctly may also prevent unwanted trespassing light and glare.

Table 1. Variables, aspects and suggested sustainability indicators (SI) or measure for the ecological impact of outdoor Light emitting diodes/solid state lighting (LED/SSL) lighting. Bold = included elsewhere.

Variable	Aspect	Suggested SI or Measure
Prevent and limit new areas being lit	Stop increases in ecological impact and light pollution	Establish and improve legislation/recommendations/guidelines
Limit the extent of illuminated areas	Reduce the ecological impact of current lighting	Shut off lights (%) Use lamp shielding (%) Eliminate overlighting **(Light loss factor (LLF), lamp lumen depreciation (LLD) or maintenance factor, Table 2)** Follow minimum values for safety (e.g., roads) Establish maximum levels for other kinds of lighting (e.g., 1 cd/m^2) **Light pollution (Table 3)**
Limit the duration of illumination	Reduce the ecological impact of current lighting at biologically critical times	Reduce lighting at critical times of biological activity (migration/ breeding/foraging) Dimming schedule Adaptive lighting with activation sensors
Limit/change the intensity of light (luminous flux/intensity)	Reduce the ecological impact of artificial light on many organisms	Luminous flux or luminous intensity per square meter (Lm/m^2; Lx/m^2; cd/m^2)
Limit/change the spectral wavelength distribution of artificial light sources		***Optical filters for wavelengths <480 nm*** ***Radiant p-band flux to photopic flux ratio (P-band)*** ***Melatonin suppression index (MSI) (Table 3)***
Sensitive areas	Reduce/improve lighting	Improve and change lighting to reduce the impact in sensitive areas

All of the above-mentioned aspects would be relatively easy to include in lighting recommendations, light management plans or environmental management plans, but require some basic knowledge on e.g., areas which should be prioritized for light pollution protection.

Preventing and limiting new areas from being lit are discussed as a sustainability indicator in relation to energy efficiency and rebound effects and light pollution in Section 5.1.3. For ecological impact and conservation of wildlife or nature reserves, this aspect is especially important to consider, but has previously been rather neglected or ignored by environmental managers and light designers and managers, despite almost one-fifth of the terrestrial world surface lying beneath light-polluted skies [48].

One major problem is that lighting systems in new areas or along new roads are not evaluated as an added system effect contributing to more light pollution and ecological impact, when in fact they are. Similarly, edge effects of light into protected areas are often ignored, whereas other aspects such as traffic and air pollution are taken into consideration. Thus, there is a need to incorporate light pollution as an ecological effect in current legislation, e.g., in environmental impact assessments or international conventions, or to produce guidelines/regulations that can be used by ecologists, environmental managers or lighting managers at different levels. In Italy, regional laws against light pollution have been enforced in 15 regions [49]. Based on that experience, Cinzano [49] recommends that the following aspects be considered for enforcement of regional laws: Lighting laws should be applied throughout the entire territory, since light propagates remotely from its source; should include private and public lighting; and should be applied for new installations. In addition, reflection by bright surfaces should be limited or reduced during specific hours, upward-directed emissions of light should be limited and other direct upward lighting, such as beams, should be prohibited. Lighting of buildings should be from top to bottom, if possible, and highly efficient lamps and professional lighting engineers should be used. Furthermore, a cap (e.g., 2%) on the yearly growth in installed night luminous flux or its power consumption can be established.

To prevent and limit new areas being lit and to stop further increases in ecological impact and light pollution, establishment and improvement of legislation/recommendations/guidelines is included as a sustainability indicator in Table 1.

It is important to control and reduce the extent of the illuminated area in order to limit the ecological impact of light pollution. This can be accomplished by turning off lights at specific times during the day or by using shielding to reduce trespassing light or glare. It is also important to eliminate overlighting. The amount of completely shut-off light can be estimated as a percentage of total lighting installation, and the same goes for the use of lamp shielding. Shielding and light trespass are discussed further in Section 5.1.3. Gaston *et al.* [45] notes that it might be beneficial to have a heterogeneous distribution of light (low luminance uniformity), since this creates dark refuges for organisms between lamp posts. However, this contradicts current road standards, which demand a minimum luminance uniformity for safety reasons (for example [50]). This shows the importance of adapting the lighting design to the specific area and the objective of the lighting, instead of routinely using standard recommendations.

To ensure that overlighting is not taking place, it is important to use the correct maintenance factor or light loss factor, so that installations are not overlit from the start. This is further explained and discussed in the energy efficiency Section 5.1.2. Regarding minimum regulations, Cinzano [49] recommends not exceeding minimum values for average luminance when such are required for safety reasons and enforcing a maximum luminance of 1 cd/m^2 for all other kinds of lighting. Thus, sustainability indicators on extent of illumination, shut-off lights, use of lamp shielding, eliminating overlighting, use of minimum values for safety and establishment of maximum levels for other kinds of lighting are suggested in Table 1.

For limiting the duration of light, LED/SSL techniques are much better suited for dimming schedules than, e.g., HPS, LPS and also other high-intensity discharge (HID) lamps. Changing the patterns of use to save energy has been suggested [51]. For organisms, the hours after dusk and before dawn have the most significant lighting impact, but these coincide with human travel peaks, when good lighting is considered most important [45]. To limit the ecological consequences of lighting, it is possible to dim at critical times of biological activity, but then specific knowledge is needed for different organisms on e.g., patterns of migration, breeding and foraging. However, such information is very difficult to collect and aggregate due to the large variations between and within species, taxonomic groups and geographical areas.

For roads, dimming schedules are restricted by the need to comply with international or national regulations/standards in order to fulfill traffic safety conditions (see Section 5.3.1). Other kinds of lighted areas may be restricted by social demands for lighting. One good example is to implement adaptive or on-demand lighting that is turned on with motion sensors or other signals, thus enabling lighting only when people actually need it. Adaptive lighting is especially suitable for different kinds of transport corridors that are less frequently used at certain times during the day [52] and perhaps also in non-residential areas. Other lighted areas such as public buildings and monuments, parking lots, industrial areas, sport centers and commercial centers should use dimming, adaptive systems or shut-off for lighting during times when it is not fulfilling any purpose and/or there is only sporadic use of the areas.

Limiting or changing the intensity of the artificial light (the luminous flux) is an efficient way of reducing the ecological impact on certain organisms (directly or indirectly via light pollution), whereas the ecological impact on more sensitive organisms will not be greatly reduced. For example, nocturnal organisms (active at night) such as insects or bats have been identified as being especially negatively affected by artificial light and such organisms may require additional measures in order to decrease the ecological impact of artificial light. By reducing the intensity of artificial light (luminous flux/intensity) per square meter (m^2), it is possible to minimize the ecological impact on many organisms and at the same time save energy, and this is therefore included here as an SI (Table 1). Depending on the stage of lighting and data availability, the suggested SI can be Lm/m^2, lumen per square meter, or Lx/m^2, lux per square meter, cd/m^2, luminance per square meter can be used.

The most commonly used LED for outdoor lighting is white and broad-spectrum LED lighting with peaks in the blue and green bands [53]. Broad-spectrum artificial lights are thought to enable organisms to perceive more light [45] and are therefore likely to increase the potential ecological impact. The increased light emitted in the blue-rich and UV bands may cause further ecological damage due to the sensitivity of ecological and biological processes, e.g., circadian rhythm, to those wavelengths, e.g., [45]. It is therefore argued that the blue-rich wavelengths in LED should be filtered out, eliminated or reduced [9,45,54]. Sustainability indicators for blue-rich and UV light are discussed and proposed under light pollution (Section 5.1.3), but are also included here (Table 1).

For particularly sensitive areas, lighting should be improved and changed in order to have minimal ecological impact. Such areas include national parks, nature reserves and protected areas. This is included as a SI, in order to improve and/or change the lighting in such areas.

There are also a number of special lighting designs that deserve to be discussed, e.g., the ecological impact of tall buildings and bridges [55]. A detailed in-depth study on these would be valuable but would require analyses of the literature and discussions with lighting designers and ecologists, and was therefore considered beyond the scope of this paper.

5.1.2. Energy Efficiency

Replacing traditional lighting systems with LED lighting generally leads to energy savings due to higher luminous efficacy, lower power consumption and longer lifespan of LEDs. Increased energy efficiency of outdoor lighting through implemented legislation and labelling has been introduced in EU through the Directive on Ecodesign of Energy-related Products [56] and labelling of lamps in different energy classes [57].

Large energy savings via dimming or intelligent controlling systems are very easy to achieve with LEDs. However, while it is obvious that the energy savings may be significant, the details of dimming in time-of-day schedules and the lighting levels are very crucial in order to maintain road lighting recommendations, reduce the ecological impact and light pollution and maintain traffic safety, visual performance and social demands. Dimming and intelligent systems are therefore discussed under those areas of interest, so that various aspects of dimming implementation are highlighted.

For road lighting system evaluation, Boyce *et al.* [51] recommend an agreed metric for road lighting energy efficiency, for example kW/Lx/km or kW/cd/m^2/km. However, there is currently no internationally agreed system of energy efficiency for road lighting, although work on this is underway, e.g., (Standard EN 13201-5: Road Lighting—Part 5: Energy Efficiency Requirements). There are some suggestions on how to calculate the energy efficiency of road lighting based on published research [33,58], where calculations of are evaluated. Calculation of energy efficiency is based on following measurements [33,58]:

- Road width RW (m), lamp pole spacing S (m) and area of the illuminated road A [m^2]
- The power of each luminaire P (W)
- Number of each luminaire type n
- Average luminance of the road surface L (cd/m^2)
- Duration of road lighting operation t (h/year)

After that, installed power load, power density, normalized power density, energy consumption, energy density and normalized energy density are calculated.

For evaluations of sustainability, however, such calculations may be too advanced for decision-makers and planners and therefore use of kW/Lx/km or kW/cd/m^2/km, or a metric based per year is suggested (see Table 2). The metric of energy efficiency of road lighting can be calculated prior to installation, in the lighting design stage, or in the verification stage when estimating energy efficiency for upgrading or replacement. To calculate the kW/Lx/km or kW/cd/m^2/km, it is necessary to know the power of each luminaire, luminaire spacing (meters), road width (meters) and calculated or measured illuminance (lux) or luminance (cd/m^2).

Measurements of the illuminance or luminance of road lighting can be very time-consuming when following the standard in detail, and therefore use of a new technique such as luminance digital technique is recommended for measuring luminance, where mean values can be obtained very quickly for the whole area of the illuminated road, e.g., [32,59]. Another possibility is to take a few representative illuminance measurements with a standard lux meter and calculate the mean values. However, there are no available standards to do such measurements currently, but it would be useful if such could be developed in order to facilitate the use of illuminance measurements for laypersons.

Table 2. Variables, aspects and suggested sustainability indicators (SI) or measure for the energy efficiency of outdoor LED/SSL lighting. Dimming is also mentioned in Table 1. Italics = data not available.

Variable	Aspect	Suggested SI or Measure
Energy efficiency	Energy efficiency based on energy and light per km road (per year)	kW/Lx/km or kW/cd/m^2/km or kWh/lx/km or kWh/cd/m^2
Mesopic design or spectral distribution of the light source	Maximize visual performance and energy savings	*Scotopic/photopic (S/P) ratio* Correlated color temperature, degrees Kelvin (K)
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 Intelligent lighting to control LLF
Reduced energy consumption by controlled dimming	Energy savings in accordance with demand	Yes/No Percentage savings (kWh/year)
Direct and indirect rebound effects	Predicted energy savings will be underestimated	Percentage (rebound effect) Number of luminaires/area New luminaires in non-lit areas
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

Mesopic design has the potential to save energy by adjusting the spectral distribution and light energy and thereby maximizing the conditions for human vision. Photopic photometry is often used in the standards for lighting design and is based on vision under well-lit conditions (from 5 cd/m^2 and at spectral lengths of 380–830 nm, with a peak at 555 nm), dominated by the use of cone cells in the retina. For human vision under very low light conditions, scotopic vision is used and the vision is then based on the rods in the retina, with a peak at 507 nm. For vision under intermediate lighting conditions such as dusk/dawn or in artificial light, mesopic vision is used and both the rods and cones in the retina are used in combination. By adapting the wavelengths of the artificial light in accordance with the peaks for human vision under mesopic light conditions, the outdoor lighting would be more optimal for mesopic vision [60]. For example, light sources with higher S/P ratios (and high correlated color temperature) but lower wattage can be used and still provide equivalent levels of perceived brightness and visual acuity.

To calculate mesopic values, it is necessary to know the background photopic luminance (adaptation luminance) and S/P ratio [61]. Light sources with a high S/P ratio commonly have a greater part of their output in short wavelength regions [60]. Thus, increased visual performance with white (or blue) light is possible at lower power effects than e.g., with yellow light. The higher the S/P ratio, the better the light source from a mesopic design perspective. Thus, S/P ratio is a good indicator of the visual performance of a light source. However, the S/P ratio in LEDs can vary from, for example, 1.16 to 2.18 depending on the product [61], and there are currently no stated "normal" limits of S/P ratios for LED light sources. Correlated color temperature (CCT) and general color rendering index (CRI) are also influenced by differences in spectral distribution and CCT is typically lower for light sources with low S/P ratios. While CCT and CRI data are usually supplied by manufacturers, information on S/P ratio is not. However, as Ylinen *et al.* [61] point out, there are shortcomings with the CRI of LED due to their peaked spectrum. It is therefore suggested that S/P ratio and CCT be included as sustainability indicators to monitor and estimate the visual performance when aiming for energy savings by mesopic design. LED manufacturers and producers should be able to easily compute and present S/P ratios for their products, since they know the spectral distribution of their lamps.

Lumen maintenance and light loss factors (LLF) represent the decline in lumen output over time, which can be attributed to decreases in lamp emissions and changing surface properties with age. Light loss factors are calculated in the design process of a road light system to ensure the light will not be below the recommended level at the end of the system's life. Consequently, most lighting systems have higher light levels than recommended in order to ensure that the levels are still adequate when the lighting system is old. The LLF include factors such as maintenance, site-specific conditions, lamp lumen depreciation, luminaire dirt depreciation and lamp burnout [62]. With an intelligent LED system, it is possible to control the level of lighting to ensure there is no unnecessary energy waste at the start (by reducing levels at the start and increasing them at the end of life). A lighting system that is overlit may also result in glare, light pollution and light trespass. Thus, intelligent lighting or controlled dimming not only saves energy during the use stage, but also controls LLF.

Royer [62] investigated the consequences of current design practices for LEDs and examined alternatives to current approaches in order to establish lamp lumen depreciation (LLD) for LED. By increasing the recommended levels of LLF closer to 1 in the design process, it would be possible to reduce potential energy waste and have fewer luminaires in the design process. For non-LED light sources, the maintenance factor is usually between 0.67 and 0.85 [52]. An LLF of 1 implies there will be no LLF during the life-time of the lighting systems at all. This will save energy and also resources, by reducing the need for lamp post installations. There is a risk that the lighting systems will provide too low levels of light at the end of life, but on the other hand, since LED and SSL technology is developing rapidly, there is a huge risk of the lifetime of lighting systems being overestimated. It is highly likely that the lamps or lighting systems will be replaced by more efficient LED lamps earlier than planned due to improved quality and lower prices in the future. Unfortunately, it is difficult to obtain values for LLF, LLD or the maintenance factor for technical reasons, since the lamp manufacturer seldom knows all the conditions in the field. Thus, manufacturers normally only state the service life for each product.

The sustainability indicators suggested here are LLF and LLD, as well as intelligent or dimmable lighting (Table 2). Energy use by controlled dimming is also included in Table 2 because reduced lighting may substantially increase the potential energy efficiency over time and because it will reduce energy when in use, but is already included as an indicator under ecological impact (see Table 1) and discussed in other sections as well.

The energy efficiency of artificial lighting has been shown in the past to lead to increased luminous efficacy, lower prices and an increased demand for lighting [63,64]. This is because when prices for the new technology decreases, consumption increases. Thus, an energy efficiency measure or policy may result in increased energy consumption, or the energy savings may be overestimated. The difference between projected and actual energy savings is called the rebound effect. When the rebound effect is above 100%, it is called a backfire effect, e.g., [35,65]. With regard to indoor lighting, it is possible that the demand for light has been met, resulting in very low rebound effects. For outdoor lighting, however, substantial rebound effects seem more or less unavoidable when more efficient and cheaper technology enters the market, e.g., [66]. From a historical perspective, rebound effects of outdoor and public lighting have occurred [63,64,67]. Due to the seemingly unmet demand for outdoor lighting, infrastructure expansion and LED/SSL technological development, there is a high likelihood of rebound effects for outdoor lighting and this will probably lead to increased energy consumption and feedback effect on other indicators. It is therefore important to include sustainability indicators that can be used to highlight, control or reduce rebound effects. Rebound effects can be calculated before/after lighting installations or other changes (e.g., intelligent systems/dimming, change of light source or change of lamps) or for a specific area (number of luminaires/area), but also by the number of new luminaires in a previously unlit area or space.

Rebound effect is calculated in accordance with the following example. A 10% reduced energy consumption is anticipated to be achieved by implementing a dimming schedule within an area. However, inhabitants or lighting owners spends the saved money from the dimming to buy new lamps and therefore increase the number of lamps within the same area, which in turn results in 5% increase in energy consumption. This yields a total rebound effect of 50% [$(10-5)/10 = 0.5 = 50\%$]. Rebound effects normally need to be limited by some kind of system boundaries and it is not very useful to calculate the rebound effects of specific lighting installation systems. However, they should be calculated for larger energy systems, e.g., parts of a city, cities, municipalities, regions, counties or a country.

It is possible to reduce the energy consumption of the lighting system by changing the surface reflection of the road and thereby increasing the luminance levels needed [52,68]. This is especially useful if the system has intelligent control, thus enabling the reduction in light to match the color of pavements. At the initial stage, pavements or road surfaces are black due to the bitumen, but as they erode the surface reflection will change and the color will be more similar to the stone materials used (the softer bitumen is eroded more quickly). Stone materials used are normally lighter in color than the bitumen, making it possible to reduce the light levels. Pavements with lighter surface characteristics can be used to increase road surface luminance and lower the energy use [68]. The drawback is that such materials are usually more expensive and may cause increased light pollution. The use of brighter surfaces or intelligent lighting to compensate for surface characteristics is included as an SI in Table 2. Brighter surfaces can be measured by luminance (cd/m^2) or by the road surface reflection coefficient, and the use of intelligent lighting systems to compensate for the brighter surfaces can be estimated by energy savings.

5.1.3. Light Pollution (Astronomical Light Pollution) and Trespassing Light

This section deals with sustainability issues concerning astronomical light pollution, sky glow and how the visibility of the sky and stars is affected and impacted upon. For a discussion of direct ecological and environmental impacts of sky glow and light pollution, see Section 5.1.1. This section focuses on different indicators to monitor light pollution from an astronomical perspective and possible technical or regulatory measures to reduce such light pollution. However, any reductions in astronomical light pollution will also directly benefit ecological and social sustainability.

Light pollution occurs when unwanted light directed or reflected upwards causes the night sky to increase in brightness (*i.e.*, sky glow), thereby decreasing the visibility of the sky, stars and other celestial bodies. Sky glow is a result of light in the atmosphere being reflected back to the planet surface and occurs since light in the sky is scattered by dust, water and gas molecules. A reduction in the number of installed luminaries outdoors would reduce the light pollution. An indicator of the numbers of luminaires within an area or new luminaires is therefore important for light pollution, but is already included under energy efficiency (Table 2). Limiting the total installed luminous flux, thus forcing new lighting to become more efficient, and not increasing the total luminous flux from an area have also been proposed [9].

According to Falchi [69], 75% of the sky brightness is contributed by light from fixtures and 25% comes from surface reflection. However, for two sites studied by that author more than 90% of the artificial sky brightness came from direct light. It is common worldwide for road and street lights to have recommended guidelines on lighting levels, e.g., [51]. However, since in most cases similar guidelines are missing for other kinds of outdoor lighting, it seems important to avoid fixtures with upward light or too overlit, for example LED signs for commercial purposes. There are many other outdoor lighting structures contributing significantly to the light pollution, for example bridges, airports, parking spaces, sport centers, cultural or heritage objects (e.g., churches, water towers, monuments), transport nodes, high buildings, and commercial, industrial, architectural, aesthetic and residential lighting. Lighting from indoor locations may also contribute to light pollution by being reflected upwards (e.g., shopping centers or central streets). For non-road lighting, there is a lack of guidelines or recommendations and this is included as an indicator here in order to reduce light pollution in the long-term perspective. Such guidelines can be produced at international, national or regional levels.

Dick [47] identified five critical lighting attributes in order to decrease light pollution, amount of illumination, extent of illuminated area, degree of glare, spectrum of emitted light and duration of illumination. In addition, land use type may influence the degree of light pollution due to differences in reflective properties of the landscape, e.g., concrete infrastructure may reflect substantial amounts of light despite using fully cut-off luminaires [70].

The amount of illumination and its duration can be controlled by recommended lux/luminance levels and dimming schedules, as discussed in Sections 5.1.1 and 5.1.2. Regarding the extent of the illuminated area, lamp shielding is an efficient way to ensure that light above the horizon and at low elevations is reduced, since the light at those angles may travel long distances and contribute to unnecessary light pollution (e.g., [9]). Shielding is achieved by use of different kinds of cut-off on luminaires, for example full cut-off, cut-off, sharp or semi cut-off, depending on the amount of light emitted more than 80 degrees above the nadir, see e.g., [47,71].

For road lighting, use of shielding may reduce luminance uniformity, thereby leading to closer spacing of lamp posts and higher costs. The first LEDs lamps introduced for roads had a restricted light distribution on the road surface and low uniformity due to a dependence on individual diodes, but there is now LED lamps on the market that will spread the light more evenly and at greater distances from the road and beyond the area of intended illumination. This emphasizes the need for the development and introduction of LED lighting with various cut-off designs, and thus shielding of LED lighting is included here as a sustainability indicator.

Disability and discomfort glare is discussed in this paper under social sustainability (traffic safety, Section 5.3.1; social wellbeing, Section 5.3.3), but is also related to overlighting and trespassing light. Trespassing light is reduced by shielding and recommendations for lighting levels and design.

LED/SSL light sources have a different spectral distribution than traditional lighting and, depending on the different elements of the layers in the LED, the lamp produces spectral peaks in different areas. The shape of the spectral distribution may also vary to be more broad or with narrow peaks. The spectrum of the emitted light is discussed in light pollution research, since the switch to LED increases the dominance of spectral content in the blue wave band. Blue-rich lighting can increase the amount of sky glow due to changes in the scattering potential, leading to a 10%–20% increase when replacing HPS lamps [10]. Luginbuhl *et al.* [72] showed that despite blue-rich light decreasing more strongly with distance, the resulting visual sky glow was significantly higher throughout 300 km (which was the limit of their study). Thus, for light pollution in general, switching to blue-rich lighting should be reconsidered. However, due to the lack of standards for evaluating the spectral distribution of products, it is difficult to know which products have less blue-rich energy.

Filtering out short wavelengths (<480 nm) with optical filters in nocturnal lighting is reported to have positive effects on hormone secretion, resulting in increased sleep duration and quality for shift workers [73]. In addition, filters have been shown to have similar or equivalent potential effect on melatonin suppression and star visibility compared with HPS lamps [54]. Thus, including optical filters in the covering or glass of the LED lamps may decrease light pollution in outdoor use too. Methods for estimating the spectral content of blue-rich light have been proposed by assuming that the wavelengths 440–540 nm, called the P-band, needs to be protected and can be calculated by an indicator called the P-ratio [9]. Similarly, Aubé *et al.* [54] studied the melatonin suppression action spectrum and proposed a melatonin suppression index (MSI) and also a star light index (SLI) as indicators characterizing the spectral distribution of any lighting device. The suggested indicators are based on different spectral distributions and are not easily calculated so an established standard indicator for estimating the blue-rich light in LED/SSL light sources is urgently needed. There are currently few manufacturers that offer LED/SSL lamps without substantial energy in the blue wavelengths. Optical filters, P-ratio and MSI are included here as suggested sustainability indicators (see Table 3).

Duration of illumination is discussed in terms of ecological impact and social sustainability. However, there are great possibilities to reduce the duration of illumination for non-road lighting or to use sensors for road or street lights, e.g., the dial4light system in Dörentrup, Germany, where road lights can be controlled by mobile phones or by remote sensors [74]. Such innovative techniques are considered beneficial for limiting light pollution, because lighting systems can be fully controlled and their use can be avoided when not necessary.

Quantification of the light pollution and sky glow within an area may require substantial resources in order to analyze satellite images, but may be of interest e.g., for cities wishing to monitor their light pollution before and after measures have been implemented. Cinzano and Falchi [75] suggest a number of indicators for quantifying light conditions of the sky such as upward luminous flux, artificial night sky brightness, total night sky brightness, star visibility, loss of star visibility, number of visible stars in a clear night, sky irradiance or sky illuminance on the earth surface, radiation density in the atmosphere, and radiation density due to direct illumination. The less problematic way of measuring sky brightness and light pollution is to analyze loss of star visibility and the number of visible stars in a clear night. A comparison is made between a star map (simulating pristine conditions without sky glow) and the current conditions, and the resulting map shows the loss of stars. Although such maps are dependent upon observer and weather conditions, it is fully possible to use the method in e.g., a municipality and to involve inhabitants. It is also possible to use e.g., the Milky Way as a proxy for stars [76]. For an excellent or truly dark site, the Milky Way is highly visible and structured, while in a less rural area the Milky Way starts to lack its obvious structures. In a suburban area, the Milky Way starts to be washed-out, weak or invisible and in the suburban to urban transition the Milky Way becomes totally invisible. It is also possible to measure the light pollution and sky glow with a sky quality meter, which although providing high resolution are sensitive to large variations [77]. The visibility of the Milky Way and measurements by sky quality meters are included in Table 3 as indicators of light pollution.

Table 3. Variables, aspects and suggested sustainability indicators (SI) or measure for the light pollution impact of outdoor LED/SSL lighting. Italics = not available. Bold = included elsewhere.

Variable	Aspect	Suggested SI or Measure
Reduce (growth of) light pollution	Light pollution in an area	Number of luminaires/area New luminaires in non-lit area
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)
Shielding of luminaires	Reduce light pollution and trespassing light from luminaires	Full cut-off, cut-off, semi cut-off and sharp cut-off design
Reduce blue-rich light (and UV)	Reduce light pollution by changing the spectrum of new light sources	*Optical filters for wavelengths < 480 nm* *Radiant p-band flux to photopic flux ratio (P-band)* *Melatonin suppression index (MSI)* *Star light index (SLI)*
Reduce duration of illumination	Reduce light pollution by innovative design	Innovative technology (for example controllable by the public) and/or activation sensors
Sky glow and sky brightness	Measure and monitor the light pollution effects	Loss of star visibility Number of visible stars Visibility of the Milky Way Measuring with sky quality meters
Regulations for light pollution	Reduce light pollution	Maximum levels of permissible illuminance or luminance for different lighting applications and their reflection
Barriers	Reduce light trespass and pollution	Barriers to stop trespassing light Specially designed lighting to avoid light trespass in adjacent areas

There are several examples of national or regional initiatives to regulate light pollution, e.g., the Light Pollution Prevention Act in Korea [78]. This establishes environmental zones and “light emission standards", for example maximum permissible luminance or illuminance for different lighting applications and their light reflection. Such regulations are very useful for the development of light management plans or light pollution management plans. The Act also specifies negligence fines for violations of the standards [78].

Barriers to reduce light trespass and light pollution can also be implemented, e.g., the construction of structures, walls or vegetation to block out light in certain directions [45]. It is also possible to use embedded lights in roads to minimize light pollution into adjacent areas [79], although in that case it would be important to avoid upward-directed light.

5.1.4. Life Cycle Assessment (LCA)

A review of LCA has been conducted by the International Energy Agency Energy Efficient End-use Equipment (IEA 4E) to investigate the environmental aspects of SSL [25]. The review focused on environmental impact of the whole life cycle, analyzing the strongest contributors to the environmental impacts, comparing the LCA of SSL with other lighting technologies and identifying the main problems when performing LCA of SSL lamps/luminaires. The review did not include an evaluation of the effects and impacts of light pollution because the analyzed LCAs did not contain it.

The review concluded that in general, 85% of the environmental impact is connected to the use phase, 15% to manufacturing and end-of-life treatment, and only 1%–2% to the transport phase [25]. The two most significant parameters of the environmental impacts were reported to be luminous efficacy (Lm/W) and useful life (*i.e.*, hours of operation during lifetime), and thus these are included here as SI (see Table 4). Luminous efficacy is a light source characteristic and is estimated by the ratio of luminous flux produced to power supply [36], and can be estimated by Lm/W, lumen per watt for a luminaire. Luminous efficacy therefore describes how well a light source produces visible light in relation to the consumed energy. Data on lumen/W and hours of operation during lifetime is generally available. One critical aspect of the environmental benefits of LED/SSL lighting is therefore the life span, which needs to be correctly quantified.

Another important aspect is the energy production (the mix of electricity generation) in a region and how the energy used for LED/SSL lighting is produced (renewable or non-renewable) [25]. However, decision-makers and planners usually do not decide their energy production supplier, since energy is procured in other parts of the organization. It is therefore not easily included as an SI. Furthermore, quantification of energy consumption and CO_2 emissions for the whole life cycle of LED/SSL lamps or lighting systems is extremely difficult, since many factories and suppliers do not wish to reveal such information or the information is lost in the many steps in the process. Instead, therefore, energy consumption and CO_2 emissions in the use phase of the lighting system (energy in kWh and CO_2 in kg CO_2 equivalents) are suggested here as SI (see Table 4). Energy and CO_2 may also be calculated as part of the life cycle costs for LED/SSL (see Section 5.2).

Energy consumption, E, for lighting is calculated as

$$E = (P \times t)/1000 \qquad (1)$$

where P is power (in watts, W) and t is hours (h) of burning during the lifetime according to producer. For example, a LED lamp has a projected life span of 50,000 h and a power of 10 W, which gives a calculated energy consumption during the lifetime use phase of 500 kWh.

CO_2 emissions can be calculated based e.g., on the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) methodology, where the average emissions are calculated based on the current generation mix (in t CO_2/MWh) and for a specific year [80,81].

Table 4. Variables, aspects and suggested sustainability indicators (SI) or measure for life cycle analysis (LCA) of outdoor LED/SSL lighting. Italics = not available.

Variable	Aspect	Suggested SI or Measure
Luminous efficacy	Luminous flux and power (energy consumption)	Lumen/watt (Lm/W)
Life cycle	Longer operating life will save resources	Hours of operation during lifetime (hours)
Energy and CO_2	Energy consumption or CO_2 for the use phase	kWh (energy) kg CO_2 (CO_2)
Energy production	Environmental impact will be reduced by use of renewable energy sources in the use phase	kWh (energy) Solar or wind-powered lights
Raw and rare materials	Non-renewable resources in the manufacturing process	*Heat sink of aluminum* *(kg or kg-equivalent antimony (Sb))* *extraction impact*
Waste material	Impact, reuses and recycling of components. Includes aspects of hazardous waste and possibilities for recycling	*kg (of waste product)* *Hazardous waste* *Recycling*

In the manufacturing process, the highest environmental impact in the LCA is linked to the aluminum parts (e.g., heat sink), electronics (the circuit board and the driver) and packaging [25]. With regard to the environmental impact of the extraction of raw and/or rare materials (rare earth elements such as indium, yttrium, cerium) used in the manufacture of an LED phosphor (the luminescent component), little information is available and this area therefore represents a data gap in the LCA. Since the use of aluminum and rare earth elements may have a significant impact on the sustainability of a product, it is necessary in the future to enhance basic knowledge within this area. However, technological advances are occurring rapidly and there are already heat sinks without aluminum or with a reduced amount of aluminum [25]. To further reduce the environmental impact from manufacturing, it would be beneficial to replace aluminum in heat sinks with renewable materials or materials with less environmental impact from extraction and processing, since much of the energy and environmental impact comes from manufacturing of the heat sink from raw materials.

Whether or not the heat sink is made from aluminum is therefore included here as an SI (Table 4). The rare elements used in phosphor manufacture are more difficult to replace, since layers of non-phosphor also contains rare elements, e.g., [82]. Use of raw and rare materials is therefore included in Table 4 as an SI, with units of “kg” and “extraction impact”, but marked with italics since it is not possible to obtain such information from manufacturers under present circumstances.

Waste materials of LED lamps in the end-of-life phase have been assessed in the USA through leaching tests, which revealed high levels of e.g., copper, lead, nickel and silver, resulting in classification of LED lamps as hazardous in accordance with California and US federal legislation [83,84]. However, the leaching characteristics depends upon lamp type. The concentrations of regulated elements in LED lamps have been shown to be similar to those in other electronic devices, such as mobile phones [25,85]. In Europe, LED lamps must be disposed of in a dedicated collection system for waste electronics, and not in the normal household waste [57]. Thus, it is important to include different aspects of waste disposal as an SI, since this may speed up the development of methods for recycling LED lamps. There is a need for an efficient recycling system for end-of-life products of LED/SSL in the future [86].

Another aspect in LCA is to develop a system for environmental labeling of LED/SSL products. If such labeling were based on LCA, it would be easier for consumers or decision-makers to include general environmental impact in their choice of products. Currently however, no such environmental labeling exists and comparing LCAs from different studies is associated with great difficulties due to, e.g., lack of detailed data and other uncertainties [87].

5.2. Economic Sustainability

This section deals with economic sustainability and LCC, payback time, economic growth, savings from dimming, cost-benefits and external costs.

5.2.1. Life Cycle Cost (LCC) Analysis

Life cycle cost analysis is an efficient calculation method for comparing the total cost of lighting systems and identifying the most cost-effective system among those available. However, due to the high pace of development and uncertainties in, for example, prices, luminous efficacy, and cleaning costs, the maintenance costs may be difficult to calculate correctly [61]. Getting verified information from manufacturers about longevity may also be a difficult issue when aiming to perform a complete LCC [5]. For LED lighting, the initial cost of buying a new system is quite high, which makes LCC even more important since 90% of all operating costs are attributable to energy consumption [5]. LCC can be calculated as

$$\mathrm{LCC} = \mathrm{Cb} + \mathrm{Cm} + \mathrm{Ce} + \mathrm{Cr} - \mathrm{RV} \tag{2}$$

where (Cb) is the cost to buy which includes the purchase price of the bulb or system and the installation costs, (Cm) is total maintenance costs total which include repair and cleaning of the fixture in order to keep it in operating condition, (Ce) is the cost of energy to run it for the life span of the fixture, (Cr) is the costs of replacing the lamp and (RV) is residual value.

This equation of LCC is included as an SI in Table 5 and can be expressed in monetary values. It should be noted that a good design of luminaire and fixtures will reduce maintenance costs. For example, if a luminaire is easy to open without tools or if the lamp is easy to replace, working time can be reduced. If luminaires are of standard IP65 or higher they require less maintenance since they are more resistant to dust and water. Steel lamp posts that are fully galvanized have lower total costs than painted steel posts [52].

5.2.2. Payback Time

The simplest way to calculate payback time is to divide the cost of investment by savings from the investment. This simple payback (SPB) calculation does not take into consideration the time value of the money, or all the cash flows. The SPB is expressed as

$$\mathrm{SPB} = \mathrm{Ci}/(\mathrm{S}/\mathrm{t}) \tag{3}$$

where Ci is investment costs, S is savings and t is time, in this case year. Investment costs for new road lighting are generally purchase of lamps, control gears, luminaires and poles, and the installation costs.

A more advanced method is discounted payback (PB), in which the time value of money is included [88] and is calculated as:

$$PB = \frac{-\ln(1 - (\frac{iC_i}{C_{o,\,old} - C_{o,\,new}})}{\ln(1+i)} \tag{4}$$

where (i) stands for rate of interest, (Ci) is the sum of investment costs, (Co) is the operating costs either for the (old) installation or the (new).

When renewing wiring and lamp posts, the original installation costs can be considered part of the investment costs, as can the disassembly costs for the original installation. Generally only the disassembly costs are considered to be part of the residual value of the original installation [61]. It should be noted that the calculation of payback time is dependent on energy prices. If the energy price is high, the savings are greater and therefore the payback time shrinks.

Table 5. Variables, aspects and suggested sustainability indicators (SI) or measure for the economic sustainability of outdoor LED/SSL lighting.

Variable	Aspect	Suggested SI or Measure
Life cycle costs	Economic comparison of lighting products	Life cycle cost analysis (LCC, monetary value)
Pay-back time	Return of investments	Payback time (PB) on return of investment
Economic sustainability	Economic health and growth correlated to lighting	Regional GDP per luminaire Regional GDP per luminous flux per area
Dimming	Economic savings due to dimming schedules	Percentage energy savings per year PB
Cost benefits External costs		Savings due to the reduced number of accidents when lighting is installed

5.2.3. Economic Growth

Economic activity, for example real capita gross domestic product (GDP, a measure of national economic health) is correlated with the amount of light and light pollution for an area [89]. Economic activity can be used as an indicator of economic growth in connection or correlation to outdoor lighting for a specific region by calculating regional GDP (RGDP) per luminaire or per luminous flux and unit area (for luminous flux per unit area, see also Section 5.1.3) (Table 5). The impact of investments and economic growth may be substantial on light pollution in developing countries [89].

It should be noted that regulations on levels of light will have an economic effect on commercial and industrial life, such as the total costs of replacing existing outdoor lighting luminaires, for example with newer and more expensive lamps and fixtures. However, this will be difficult to measure. There is also a potential conflict with commercial districts that rely on window displays with bright lighting to attract the attention of customers [90].

5.2.4. Dimming Schedules

Dimming at night can reduce light pollution and reduce energy costs, for example, by as much as 40% [42]. Dimming can be achieved through a central management system which controls a large area of lighting resources. The payback time on these systems, depending on energy prices, can be as little as 4–5 years, even though they are an extra cost in an installation [91].

5.2.5. Cost-Benefits and External Costs

Road lighting generally significantly reduces the total number of accidents, *i.e.*, the number of fatal accidents and accidents causing injuries and property damage, e.g., [37]. Cost estimates of accidents can be calculated if the price of a life, injury or damage is determined, and if the number of accidents in relation to the yearly traffic work (average km driven per vehicle and year) or traffic flow is known. The costs can then be used to calculate how much money will be saved on a specific road with a certain amount of traffic with and without road lighting. This can be compared with the cost of the lighting installation and its maintenance. Such cost-benefit calculations are usually based on national statistics and are used by national road administrations when planning roads. It would theoretically be possible to conduct similar calculations for the added social or economic benefits of lighting, e.g., in squares, shopping centers, residential areas or parking lots. However, little information is available on any international agreed method or indicator to use specifically for outdoor lighting, and therefore only savings due to the reduced number of accidents when lighting is installed are included as an SI in Table 5.

Lighting causes impacts on ecosystems and humans, but the costs of such effects are not borne by the lighting owners (for example municipal, private, corporate or governmental owners). Such costs are called external and should be internalized and included in the decision-making process by buyers of outdoor lighting devices, e.g., [92]. Regarding noise and air pollution in the transport sector, there are economic calculations available that include the external costs of health impacts [93]. There are currently no external cost estimates available for light pollution. However, visitor willingness to pay for visiting dark areas such as national parks will most likely be reduced if these are affected by light pollution [89]. Furthermore, it could be argued that the aesthetic loss of the night sky could have a major economic impact, since throughout history the night sky has been a popular subject and inspiration for many artists and scientists [89]. There is currently a research gap regarding the costs of light pollution impacts on ecosystems, health, wellbeing, visual impact, light quality and livability. This rules out the use of external costs as a sustainability indicator.

5.3. Social Impact of Outdoor Lighting

The social impact of outdoor lighting is divided here into the following groups that seemed relevant based on Hall [16], with the focus on transportation, safety, human health, social wellbeing/quality of life, and equity/distributional fairness. Again, there are overlaps between sections, e.g., glare in traffic safety and in social wellbeing.

5.3.1. Traffic Safety

It is generally agreed that the presence of road lighting significantly reduces the number of fatal and serious injury accidents [14,37,94]. The number of traffic accidents is a common sustainability indicator in transport and is therefore included in Table 6. For road lighting design, the international Commission on Illumination (CIE), the Illuminating Engineering Society of North America (IESNA) and the British Standards Institution (BSI), among others, have developed standardized requirements on e.g., minimum levels of luminance, luminance uniformity, illuminance and illuminance uniformity, depending on road type. The British Standards Institution (BSI) also includes an evaluation of the S/P ratio [95]. These standardized requirements are included as sustainability indicators of traffic safety.

Table 6. Variables, aspects and suggested sustainability indicators (SI) or measure for the traffic safety of outdoor LED/SSL lighting. Italics = not available. Bold = included elsewhere.

Variable	Aspect	Suggested SI or Measure
Traffic safety	Traffic safety monitoring	Number of traffic accidents
Road lighting design traffic safety	Standard requirements for road lighting	Luminance (average cd/m^2) Luminance uniformity (minimum luminance/average luminance) Illuminance (average lux) Illuminance uniformity (minimum illuminance/average illuminance) *Scotopic/photopic (S/P) ratio*
Mesopic design	New standard for road lighting	***S/P ratio*** **Correlated color temperature, degrees Kelvin (K) (Table 2)**
Dimming schedule adaptive/intelligent lighting systems	Save energy with no traffic safety impact	Percentage of full wattage per hour (or of saved energy per year)
Glare	Estimation of glare	Glare index (GR) Threshold increment (TI) or veiling luminance **Shielding (Table 3)**
Glare	Reduce risk of exterior lighting glare	Reduce glare from non-road lighting

LED lighting has the potential to save energy by the switch to more broad-spectrum light sources and to improve color contrast and visibility. By implementing mesopic design as a standard for road and transport lighting, it would be possible to replace traditional or LED lamps with more energy-efficient products of LED/SSL, without any negative impact on traffic accidents or safety. Mesopic design is discussed in Section 5.1.2.

Dimming schedules or adaptive/intelligent systems with LED lighting can be implemented in many places without any impact on traffic safety (in particular in areas where there is no traffic during specific times) if it is possible to measure the amount of traffic hour-by-hour during the day and adapt the light levels accordingly. For roads with very low levels of traffic during certain hours, it is not necessary to always have full lighting. However, sometimes the road lighting illuminates adjacent pedestrian or cycle paths. Since pedestrian and bicycle crossings are often over-represented in traffic accidents, it is important to consider total usage of transport infrastructure before implementing any reductions in lighting levels. Since travelling patterns and road type may vary greatly, it is difficult to recommend any special dimming schedule.

Glare can be the indirect cause of accidents and since LEDs have very high radiance and illuminance compared with traditional light sources, the use of LEDs is associated with increased glare risks. However, for outdoor lighting the glare index (GR) (for high power installations) and threshold increment (TI) are considered applicable, irrespective of the light source, and are thus recommended for use with LED/SSL [26]. To decrease the risk of glare, it is possible to use shielding (see Section 5.1.3). Thus GR, TI and shielding were included here as SI (Table 6). Furthermore, commercial and non-road lighting can have very high light irradiance levels that can cause glare for vehicle traffic. Such glare sources can be controlled by identifying them and enforcing recommendations, and are therefore included as an indicator.

5.3.2. Human Health

LED and SSL lighting poses a blue light hazard due to photochemical damage to the retina caused by blue and violet light [26]. For outdoor applications, there is a very low risk of blue light retinal damage, since the viewing distance to the light source is very long. Except for a photobiological safety assessment with manufacturers labeling the risk group of their product, there does not seem to be any current indicator that can be used [26].

Flicker is a variation of the optical output of a light source and may have health effects in terms of headaches, migraine and dizziness [26]. LED lamps are considered unreliable in this aspect and may or may not have light flicker. There are currently no requirement or standards, e.g., maximum values, for light flicker in SSL products [26].

Non-visual effects of LED/SSL products may result in an impact on the human circadian rhythm/clock by affecting the melatonin levels. Retinal light exposure can decrease melatonin production at night and is linked to several diseases, for example diabetes, obesity and cancer [26,40,54,96]. These effects are dependent on illuminance level, exposure duration, timing of exposure and the light spectra [26]. Light spectra of shorter wavelengths (blue and green) may trigger or enhance the non-visual lighting effect, whereas light richer in the longer wavelengths (yellow, orange and red) is less effective in activating melatonin suppression responses. The recommendation in order to minimize the non-visual effects of light is to keep the retinal irradiance low (e.g., by total darkness during sleep), since there is no established threshold for when the non-visual system is activated, and also since any wavelength could activate the non-visual system [26,97].

Martinsons and Zissis [26] concluded that SSL technology is not likely to have a more negative impact due to non-visual effects, but that increased usage of LED/SSL products may increase the overall light exposure, indirectly causing increased non-visual impacts. Use of melatonin suppression index (MSI) or spectral distribution has been proposed, but has limited value for human impact since it does not completely describe the physiological mechanisms behind the regulation of circadian rhythms. Thus, MSI, luminous flux per area and individual light exposure levels are included here as indicators for the non-visual effects of LED/SSL or as proxies for the non-visual effects.

It is also possible to perform surveys that investigate inhabitants' sleeping habits (and disturbances) and their perceptions of light pollution (glare, sky glow) for both exterior and interior environments. Such surveys could be internet-based and addressed to inhabitants in a sub-area, city, or region, and could analyze both health effects and perceptions of light pollution.

Table 7. Variables, aspects and suggested sustainability indicators (SI) or measure for the health impact of outdoor LED/SSL lighting.

Variable	Aspect	Suggested SI or Measure
Blue and UV light hazard	Photobiological hazard	-
Flicker	May cause health effects	-
Non-visual effects of light	Impact on circadian rhythm	Melatonin suppression index (MSI) Luminous flux/area (lm/area) Questionnaire

5.3.3. Social Wellbeing, Quality of Life and Equity

Social wellbeing, quality of life and aspects of equity are discussed here in terms of criminality, perceptions, livability and equity of lighting designs.

Improved lighting can reduce crime in an area by improved surveillance of potential perpetrators (by increased visibility and increased amount of inhabitants on the streets), leading to a prohibitive effect [98]. Improved lighting may also lead to reduced criminality indirectly, through investments in refurbishment increasing the sense of pride or reassurance among residents. The social unity and control will thus increase as an indirect effect of the lighting improvements, leading to lower criminality during both day and night [98]. A meta-analysis based on 13 different studies showed that improved lighting resulted in a 21% decrease in criminality compared with control areas (without lighting improvements) [98]. Even though research correlating criminality to lighting has been questioned [99], criminality is a valuable indicator of sustainable development in different areas (Table 8).

Perceived outdoor lighting quality has been studied in an environmental psychological approach, e.g., [100,101] and is assumed to describe feelings of visibility and recognition, which are important aspects of feeling safe and non-threatened. However, perceptions of LED lighting compared with traditional light sources have not been studied explicitly in environmental psychology, but see Nikunen *et al.* [102]. Because a person's perceptions of lighting are often intermixed with perceptions of an area and its surroundings, intervention studies are the most reliable method of investigating perceived lighting quality. In such studies, the lighting is replaced and people's perceptions are investigated both before and after the switch, through e.g., a number of observer-based assessments.

Johansson *et al.* [101] developed an observer-based environmental assessment tool (perceived outdoor lighting quality, POLQ,) consisting of 10 bipolar semantic differentials, representing two indicators, perceived strength quality (PSQ) and perceived comfort quality (PCQ). Both indicators showed correlations with photometric parameters and are recommended as a complementary tool for sustainable light design [101]. For PSQ, the following differentials were used, subdued-brilliant, strong-weak, dark-light, unfocused-focused, clear-drab and for PCQ, hard-soft, warm-cool, natural-unnatural, glaring-shaded, mild-sharp. These 10 items can be evaluated on a five-point scale (in general 1 = low; 5 = high) by laypersons in the field using paper and pen. The use of a standard assessment tool for perceived outdoor lighting quality is strongly recommended to evaluate the sustainability of the social dimension of LED/SSL lighting systems and is therefore included as an indicator in Table 8.

Table 8. Variables, aspects and suggested sustainable indicators (SI) or measure for the social wellbeing impact of outdoor LED/SSL lighting. Bold = included elsewhere.

Variable	Aspect	Suggested SI or Measure
Criminality	Crimes	Number of crimes in an area
Environmental perception	Perceived outdoor lighting quality	POLQ questionnaire Illuminance (lux) *Scotopic/photopic (S/P) ratio*
Light pollution	Aspects of light pollution and discomfort glare	**See Table 3.** De Boer scale rating survey
Equity	Increase equity	POLQ questionnaire Investments in old lighting systems irrespective of location

A review on road light and pedestrian reassurance after dark suggests that both illuminance and S/P ratio are important elements of the environment and will enhance reassurance of pedestrians [103]. Illuminance and S/P ratio is included in the social well-being section in Table 8.

Light pollution can be perceived as negative visual impact or decreased light quality, leading to unwanted and intruding light. Such light pollution can interfere with people's sleeping habits, destroy the sense of privacy and influence the social wellbeing and livability in an area. There is a lack of studies showing concrete effects of perceived light pollution and such effects will probably be difficult to investigate due to the shifting baseline syndrome (see discussion below). Light pollution is discussed in Sections 5.1.3 and 5.2.5.

Discomfort glare is unwanted light that can impair vision, is annoying and may be painful. Discomfort glare is different from disability glare, which is defined as a reduction in the visibility. Discomfort glare is more difficult to measure than disability glare, but the De Boer scale, a nine-point scale with subjective ratings [104], is commonly used, although some research has been conducted to develop models for correlating photometric measurements with e.g., De Boer rating scale [105]. The De Boer scale for discomfort glare has the following equivalencies 1- unbearable, 3-disturbing, 5-just permissible, 7- satisfactory and 9-just noticeable [104]. Discomfort can therefore be estimated based on perceptions of the glare by laypersons in an organized survey. It is included as a possible indicator in Table 8.

Equity or justice is an important, but rarely studied, aspect of LED/SSL lighting. There are differences in the visibility of light and the impact on melatonin suppression depending on age. Different genders or cultural groups may have different preferences for optimal brightness or safety. There are also aspects of economic equity to consider if, e.g., complaints from residents result in improvements of lighting while other areas are not prioritized. Energy savings from new lighting in one area can also be spent on refurbishments in another area, thereby causing inequalities. To increase equity, investigations on perceived outdoor quality can be conducted, as well as considering investments in old lighting systems irrespective of their location.

6. Results and Discussion

As this review showed, there are many different aspects to consider when planning and making decisions on new LED/SSL lighting. It is important to evaluate the three sustainability dimensions together, since otherwise economic aspects may be the only consideration in decisions on products, with possible negative aspects on other areas such as environmental or human impact. In some cases, such as light pollution or dimming schedules, the indicators are all directed towards a decrease in order to be sustainable within the ecological, economic and social arenas. In such cases, there are no conflicts between e.g., environmental impact and traffic safety or social demands. In other cases, such as the blue-rich LEDs, there are direct conflicts between the areas (blue-rich LEDs are the cheapest available LED lighting on the market, but may cause ecological and/or health effects). Research gaps may lead to investments in LED/SSL lighting systems without sustainable development, causing unnecessary environmental, economic, social or health impacts.

In many cases there are research gaps, making it impossible to choose indicators for monitoring or to reduce impacts since thresholds or measurements of an impact are unknown. Such under-researched areas include the ecological effects of light pollution, health effects of light pollution and many social aspects of LED/SSL lighting. Ecological impact on various animals and organisms can be studied in planned and organized international joint research projects where the methodology should be standardized by using, for example, specific designs of luminaires, pole height, pole distance and area of exposure. The few ecological studies that have analyzed effects of LED/SSL lighting have used different methods, areas and experimental design which makes it very difficult to compare results. Standardized methodology have previously been very successfully implemented for studying simulated climate change on circumpolar and tundra ecosystems in ITEX (the International Tundra Experiment). Standardized methods could be developed and used for analyzing environmental impact in lighting research. Furthermore, standardized methods could also be used for studying health effects, LCAs or many aspects of social sustainability. The environmental impact in general needs to be more thoroughly evaluated and analyzed for LED/SSL lighting, and especially ecological and human health impacts in terms of light pollution needs to be included in evaluations, for example, in LCAs. The economic cost of switching to new lighting technology may be high in a short time frame, as is the case when municipalities or cities implement legislation with a very short implementation time (e.g., Aspen, USA; [106]). While such official rules and policies may cause additional costs in terms of replacing lighting systems premature (before they have reached payback), it is clear from this study that lighting owners and buyers do not currently pay for the external costs of their products (e.g., health effects or ecological effects). Thus, there is a need to conduct more research on LED/SSL lighting in order to give better recommendations for sustainable development and to make sure external costs are included in the price of lighting systems, and to be able to quantify the cost-benefits of having artificial lighting in populated areas.

An important reason for considering sustainability for the three dimensions concurrently is the potential for reducing light levels by exposing and evaluating different aspects. Information on e.g., the environmental impact of different lighting may increase public acceptance for lower levels of lighting [107]. Likewise, it has been shown that when social safety is not threatened, it is possible to accept lower lighting levels [108].

An important aspect in the sustainable development of outdoor lighting is the possible presence of shifting baseline syndrome [66,109]. A shifting baseline is when comparisons are performed against a reference point (*i.e.*, the baseline), but where the baseline itself is under change and may be significantly different from earlier occasions. The result is a lack of understanding of previous conditions and degradation of ecosystems or species over time being masked or unidentified. Each new generation redefines the normal/natural state and there is a loss of perception of the change taking place between generations. For outdoor lighting and light pollution, the loss of perception of change may also occur for individuals. The shifting baseline syndrome in outdoor lighting may cause increasingly higher acceptance of light pollution and increased growth of luminaires and/or wattage, thus resulting in continuous growth of light pollution world-wide. Light pollution is already increasing at a rate of 3%–6% per year [110] and very few countries or cities have identified outdoor lighting as having an environmental or social impact. By implementing a framework for decision making and planning of sustainable LED/SSL lighting, it will be possible to measure, monitor or decrease the negative impacts of outdoor lighting systems.

There are many future studies possible within the area of sustainable lighting based on this new framework of sustainable indicators. For example, by conducting research on thresholds for lighting impacts, indicators could be monitored and measured. The framework proposed here would benefit from future studies on real lighting installations, thus enabling comparisons of different LED/SSL products. It is possible that some sustainability indicators suggested here are redundant and could be excluded and that future lighting research will add more indicators to the framework, as well as improve the knowledge, metrics and units of the proposed ones. The new framework of sustainability indicators and measures should be viewed as a base for future work and improvements.

7. Conclusions

This review-based paper proposes a new framework of sustainability indicators and/or measures that can be used for evaluating or highlighting aspects of special interest when choosing LED/SSL lighting within the areas of ecological, economic and social sustainability. The following areas were examined: ecological impact, energy efficiency, light pollution and LCA in the environmental impact section; LCC, payback time, economic growth, dimming, cost-benefits and external costs in the ecological sustainability section; and traffic safety, human health, social wellbeing, quality of life and equity in the social sustainability section.

For several areas there is much knowledge available and indicators have already been proposed for measuring and monitoring (e.g., light pollution, energy efficiency, glare), whereas for other areas there are information gaps and few indicators can be suggested (ecological and environmental impact, LCA, cost-benefits, external costs and social sustainability).

There is a lack of solid evidence on the effects of outdoor LED/SSL lighting *per se*, but when rigorous and substantial research has indicated that excessive or unwanted light can be harmful, measures on reductions are suggested, when possible. For example, light pollution may cause ecological, health and social impacts and demands resources in terms of material, energy and money. In such cases there are probably no conflicts between the different sustainability dimensions. However, there are several areas that need further research in order for outdoor lighting to contribute to sustainable development in the future.

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Conflicts of Interest

The author declares no conflicts of interest.

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