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Review

Synergies and Trade-Offs Between Sustainable Development and Energy Performance of Exterior Lighting

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Abstract: The aim of this review was to map synergies and trade-offs between sustainable development and energy efficiency and savings regarding exterior lighting. Exterior lighting, such as public road and street lighting, requires significant amounts of energy and hinders sustainable development through its increasing of light pollution, ecological impact, and global climate change. Interlinkages between indicators in sustainability and energy that have positive interactions will lead to a mutual reinforcement in the decision-making process, and vice versa, interlinkages between trade-offs may lead to unwanted and conflicting effects. Very few studies have presented a clear vision of how exterior lighting should be contributing to, and not counteracting, the sustainable development of our planet. This study was conducted through a theoretical and systematic analysis that examined the interactions between sustainable development and energy performance based on a framework using indicators and variables, and by reviewing the current literature. Additionally, 17 indicators of energy efficiency and energy savings were identified and used in the analysis. Most interactions between variables for sustainable development and energy performance (52%) were found to be synergistic. The synergistic interactions were mostly found (71%) in the ecological and environmental dimension showing that environmental and ecological sustainability goes hand in hand with energy efficiency and savings. Trade-offs were found only in the economic and social dimensions accounting for 18% of the interactions identified. This review shows that the interactions between sustainable development and energy performance can be used to establish more efficient policies for decision-making processes regarding exterior lighting.

Keywords: outdoor; environment; ecological; economic; social; traffic safety; policy; legislation; street lighting; road lighting; artificial lighting; human health; sustainable development

1. Introduction

Exterior lighting, such as public road and street lighting, often requires significant amounts of energy due to the long operating hours and high wattage needed to sustain visibility, comfort, and safety [1]. The worldwide total electricity usage for lighting in 2005 represented 19% of the world's total electricity consumption for the year, of which stationary outdoor road lighting accounted for 53% of the usage [2]. At the municipal level, as much as 60 to 80% of the total electricity consumption can be attributed to street lighting [3,4], with high accompanying costs. However, exterior lighting also produces valuable benefits for humans—increased safety, attractive outdoor environments, and promotion of outdoor activities, which fosters social well-being [5]. There is a correlation between the use of light at night and economic activities (e.g., GDP) [6], indicating that economic growth may be a motivator for investments.

Nevertheless, the use of light at night generates serious negative trade-offs, such as high emissions of CO_2 and global climate change due to the high energy consumption. Other negative trade-offs from the use of lighting are light pollution, ecological impacts, glare, and obtrusive light, to mention a few. Light pollution is the unwanted, unintended and obtrusive aspects of artificial lighting and is an environmental problem of growing concern since the use of artificial light in the exterior environment continues to increase globally at a rate of approximately 6% per year [7,8]. For example, street lighting was shown to have doubled electricity consumption in most Spanish provinces over an 18-year period [9]. In addition, the encroachment of previously dark areas and the increasing extent of artificial light at night in areas with high species richness is considered "an emerging threat to global biodiversity requiring immediate attention" [10]. Ecological consequences of artificial light at night also include a significant contribution to the rapid global decimation of insects which subsequently threatens the function of nature's ecosystems [11], a range of (negative) ecological impacts on organisms, such as changes in species mortality rates and reproduction [12], and environmental degradation of ecosystems [13].

In a recently developed decision support system for assessments of street lighting tenders, one of the conclusions was that the negative effects of light pollution must be counterbalanced by action taken in road lighting projects [14]. It is therefore suggested that a decision tool should include several energy performance indicators and light pollution criteria, and decisions should be validated by photometric measurements. This demonstrates that there is an urgent need to be able to understand and carefully balance different criteria and indicators against each other in the decision-making process to make the lighting installation sustainable.

However, there are many aspects that needs to be considered simultaneously in the process of planning exterior lighting to be holistically successful. A thorough understanding of the interactions between factors that contribute to sustainability and factors that counteract sustainability will help to prioritize effective and efficient lighting design solutions conducive to societal goals, such as the 2030 Agenda and the sustainable development goals (SDGs) adopted by the United Nations General Assembly [15].

Interlinkages between sustainability indicators that have positive interactions will lead to a mutual reinforcement in the decision-making process, and vice versa—interlinkages between trade-offs may lead to unwanted and conflicting effects. This has been shown for interactions between SDGs, where goals toward energy lead to positive impacts on other SDGs, such as poverty alleviation, human health, enhanced sustainability of cities, and reduced climate change [16]. However, interactions between energy and the other SDGs were shown to be affected by context-dependencies and directionality [16,17]. Due to context-dependencies and the complexity behind the interactions, it is difficult to generalize regarding interlinkages between higher energy efficiency or savings and approaches towards sustainable development for exterior lighting.

Considering the large amounts of energy required by the world's exterior lighting, a fundamental understanding of the interactions between energy performance and sustainable development is essential to ensure that mutual reinforcement occurs for institutions and decision makers who are working toward the goals of the 2030 Agenda. Still, very few studies have presented a clear vision of how exterior lighting should be contributing to, and not counteracting, the sustainable development of our planet.

In 2015, Jägerbrand presented a framework of sustainability indicators for outdoor lighting [18]. The framework allows for the prioritization of lighting products and enables decision-making that is more in line with the long-term SDGs established by society or organizations. When analyzing the sustainability aspects of exterior lighting, some obvious negative trade-offs with goals towards increased energy efficiency or savings were identified. For example, the use of energy-efficient broad-spectrum LEDs is thought to increase the ecological harm of artificial light as it enables organisms to perceive more light [12,19–21]. Similarly, synergies (or cobenefits) between energy savings and sustainability were also identified in, for example, the implementation of smart and adaptive lighting technologies that reduce energy consumption and light pollution. Trade-offs between sustainability and energy efficiency may result in lower rates of adoption and diffusion of more energy-efficient technology but may also lead to suboptimal lighting designs. The synergies, on the other hand, are positive aspects that could lead to increased investments in energy-efficient products or technologies, as the goal of sustainable development would then reinforce and strengthen energy goals. Synergies will therefore lead to mutual reinforcements in energy efficiency or savings and a sustainable development.

Despite international and national goals on reducing energy consumption, greenhouse gases, and global climate change, no previous study has analyzed the interactions between energy and sustainable development in a systematic and comprehensive manner that managed to include all hitherto identified indicators in the dimensions of sustainability.

Consequently, the aim of this review was to map synergies and trade-offs between sustainable development and the energy efficiency and savings of exterior lighting.

In this paper, a theoretical analysis was performed in which sustainable development variables and indicators were assumed to change in a beneficial direction towards improving sustainable development. The subsequent interaction between sustainable development and energy efficiency and savings were classified as synergistic, neutral, unknown, or as a trade-off. The classifications were based on the current scientific literature.

A minor systematic literature review was also performed to ensure that all relevant energy "performance" variables were included in the analysis (for more information, see Section 4). The analysis of interactions was based on the framework of sustainability indicators for outdoor light emitting diodes (LEDs) and solid-state lighting (SSL) [18], which covers the ecological and environmental, economic, and social dimensions but is restricted to LEDs and SSL. It contains 54 sustainability indicators in the environmental dimension, six in the economic dimension, and 24 in the social dimension.

This article is structured as follows. In Section 2, the materials and methods used are described. Section 3 describes the theoretical framework of sustainable indicators for exterior lighting. The energy performance of exterior lighting is defined in Section 4. The results obtained are discussed and presented in detail in Section 5, and finally, the overall conclusions are presented in Section 6.

2. Materials and Methods

The study was conducted by performing a literature review to identify indicators of energy performance (i.e., variables, aspects, indicators, and types of variable) and through a theoretical and systematic analysis and review examining the interactions between sustainable development and energy performance based on a framework.

2.1. Literature Review of Energy Performance of Exterior Lighting

On the 16 September 2019, a systematic literature search was conducted using the online databases Scopus and Web of Science. The search terms were organized in two groups; the first group was based on energy-related terms, and the second group was based on outdoor and lighting-related terms. More specifically, (group 1) consisted of "energy efficie*" or "energy savings" or "luminous efficie*" or "efficient energy use" or "energy conservation", and was combined with (group 2): "exterior light*" or "outdoor light*" or "street light*" or "Road light*" or "LED light*" or "High pressure sodium" or "Metal halide" or "lamp". The use of truncation (*) indicates the varied endings of words included in the searches. For example, a search on "energy efficie*" resulted in hits on both "energy efficiency" and "energy efficient". The searches included the years from 2010 to the present, all document types, and English papers only. The searches were executed only in the title field to restrict the number of hits. All hits were imported into an EndNote library so duplicates could be excluded. The systematic searches yielded a total of 297 hits. Titles were screened for relevance and full texts were read only when assessed as relevant for the scope of this paper. Additional literature was identified through the "snowball effect" (using references and citations in publications) and through previously known literature.

2.2. Analyses

The sustainability indicators (SIs) from the framework of sustainable development were used as a basis for analyzing interactions with energy performance variables in a systematical way. However, since the framework of SIs is highly redundant, the SIs were clustered together for the same variable when the SIs were determined to have the same impact on the interaction with the energy performance variables. The clustering was an iterative process during the analyses of the interactions between the energy performance variables and the SIs. When SIs belonged to the same variable but had different interactions with the energy performance variable, they were not clustered. The variables and indicators and their area of activity that was used in this paper are available in the Tables A1 and A2.

The interactions between the energy variables and indicators and the sustainability variables and indicators were analyzed systematically with a theoretical comparison. More specifically, for each sustainable variable and indicator, an analysis was performed against each of the energy performance variables and indicators. This was conducted under the assumption that the sustainability indicators would change in a wanted (sustainable) direction (for example, decrease or increase) and that a change would or would not impact the energy variables and indicators.

If the change in SIs negatively impacted energy performance, it was classified as a trade-off; if it resulted in a positive impact it was classified as synergistic, as shown in Table 1. When no clear conflicts or synergies could be determined, the interaction was classified as neutral. The categorization of interactions used in this paper is in line with previous studies that mapped the interactions between sustainable development goals [22]; trade-off is comparable to counteracting or canceling; synergy is indivisible or comparable to reinforcing or enabling; neutral is comparable to consistent (no significant interactions). In cases where it was not possible to fully determine the interactions due to insufficient data, the interaction was deemed to "unknown". Impact on SIs can theoretically be classified as direct or indirect, as well as unidirectional and bidirectional, but to limit the analyses, only direct impacts were considered. During the process, literature searches were conducted successively to find evidence of the interactions between sustainable development and energy performance. The literature searches included both queries for scientific literature (in Scopus and Web of Science) and nonscientific literature through Google using relevant key words for the indicators and energy.

Table 1. Description of classifications on the interactions between sustainable development and energy performance for exterior lighting.

Interactions	Description
Trade-off	An improvement or change in the sustainability indicator results in a negative impact in energy performance. For example, consumption of more energy.
Synergistic	An improvement or change in the sustainability indicator results in a positive impact in energy performance. For example, decreased consumption of energy.
Neutral	An improvement or change in the sustainability indicator does not result in conflicts or synergies that can be easily identified (i.e., no direct relationship).
Unknown	It is not possible to fully determine a relationship between the sustainability indicator and energy performance due to insufficient data.

3. The Framework of Sustainability Indicators (SIs) for Exterior Lighting

The framework of sustainability indicators (SIs) for outdoor lighting was proposed in 2015 and is based on a literature review that established variables, aspects and indicators [18]. LED/SSL lighting was reviewed from a conventional sustainable development perspective, i.e., covering the three dimensions: ecological and environmental, economic and social sustainability. Compared with the more over-arching SDGs in the 2030 Agenda that can be employed at national and international levels, the SIs framework is much more detailed because the indicators have been identified and developed with a particular focus on exterior lighting.

Indicators were chosen to provide a solid basis for decision-making and to ensure that goals, objectives, and targets can be measured, monitored, and fulfilled. As such, any indicator must be a specific variable from a value or a measurement based on a scientific concept that can be quantified in an objective manner. It is also possible to include indicators that require a yes or no answer, for example, the use of lamp shielding to minimize ecological impact. Such indicators can be used to increase lighting quality for indicators that cannot easily be determined but are believed to be significant for sustainability. In the SIs framework, the focus was on the categories input, output, impact, and reduction, which were then combined with the three dimensions of sustainable development. In some cases, the indicators were chosen to be representative of reduced impact rather than indicators for measuring, for example, concerning ecological impact and light pollution.

The constructions of SIs are informed by the metrics and causal relationship between the variable and the indicator. Thus, if there is a lack of empirical evidence regarding the relationship between lighting and responses or impacts, it is not possible to use an indicator for the variable, irrespective of its importance for sustainability. The framework of SIs should therefore be viewed as a base for future work and improvements, and not as a final product. Successively, new knowledge or standards will contribute with additional indicators to the framework.

The ecological and environmental dimension includes ecological impact, energy efficiency, astronomical light pollution, and life cycle assessment (LCA) shown in Figure 1, and consists of 54 indicators in total. Light pollution in the framework is divided into ecological light pollution and astronomical light pollution and trespassing light. While light pollution in general includes various aspects of unwanted light, ecological light pollution is defined as “artificial light that alters the natural patterns of light and dark in ecosystems” [23], and will likely result in an ecological impact. Astronomical light pollution and trespassing light concerns, for example, sky glow and how the visibility of the sky and stars is affected and impacted upon.

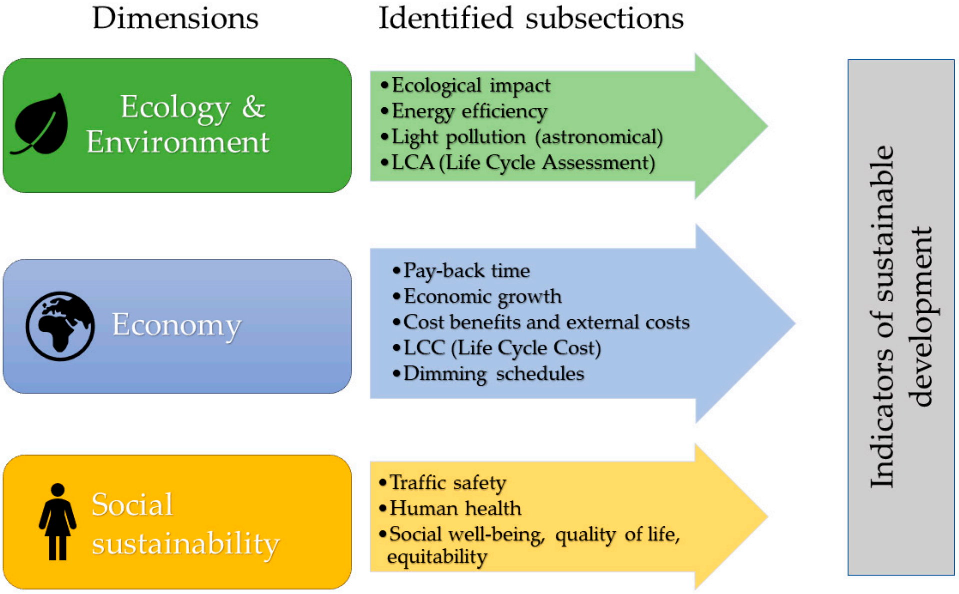

Figure 1. Overview of the dimensions and hitherto identified subsections in the framework of indicators of sustainable development for exterior lighting [18].

Life cycle cost (LCC), pay-back time, economic growth, dimming schedules, cost benefits and external costs represent both variables and indicators that are included in the economic dimension, as shown in Figure 1. The dimension of social sustainability comprises traffic safety, human health, and social well-being, quality of life and equitability as shown in Figure 1, and includes a total of 24 indicators. However, the ecological and environmental impact, LCA, cost benefits, external costs, and social sustainability were all identified as having substantial knowledge gaps that resulted in relatively few suggested indicators [18]. Many indicators were also found to overlap.

For the purpose of this study, it was necessary to reduce the number of SIs to avoid redundancy. The final list consists of sustainable development variables, 18 in the environmental dimension, 5 in the economic dimension, and 10 in the social dimension. The list of variables and indicators used in this analysis is available in the Tables A1 and A2.

4. Energy Performance of Exterior Lighting

It has long been debated whether an improved energy efficiency generally results in reduced energy consumption [24]. An improvement in energy efficiency does not automatically lead to a lower overall energy demand or to a lower energy demand compared to an unchanged use of the service or goods. This is because improved energy efficiency also leads to changes in prices and market demand, which will result in greater use (e.g., from behavioral or other systemic responses), called the rebound effect or takeback effect.

In the context of exterior lighting, an example of the rebound effect is the introduction of energy-efficient lighting source technologies leading to energy savings which also leads to a higher general use of lighting in the same area with, for example, complementary lighting, such as accent lighting, façade lighting, uplights, parking lot lighting, and so on. Hence, the calculated energy savings are decreased by the increased use of luminaires and energy, resulting in a reduction in expected gains from the new technology. The rebound effect can be calculated as the difference between the projected energy savings from the increased energy efficiency and the actual savings. The rebound effect has been thoroughly investigated for light sources in the outdoor environment during the past three centuries. Technological development has brought about an increased luminous efficacy that has been accompanied with an increased demand for energy for lighting, resulting in an overall rebound effect of 100% [25,26]. It is therefore important to consider the possibility of rebound effects when analyzing the relationship between energy efficiency and aspects of sustainability.

Improving the energy efficiency of exterior lighting requires consideration of several areas, from the planning process to the user end phase. A great deal of research has been conducted with a focus on energy and exterior lighting—e.g., light sources [27,28], intelligent and smart systems [29,30], control systems [31], dimming [32,33], optimization [34–36], quality needs [37,38], energy performance indicators [39–41], and evaluations [1,42–44]. Other studies have examined combinations of factors, e.g., a change of light source and dimming [45]. Energy savings of road lighting were identified in four different areas when examined with the aim of preserving the benefits while minimizing energy consumption for UK conditions by Boyce et al. [46]. The four areas of change for energy savings suggested by Boyce et al. [46] were technology, patterns of use, standards and contracts, and the basis of design.

Energy performance can, within the context of this paper, be described as a measure of the relative efficiency of the exterior lighting service. Energy performance can therefore describe both energy efficiency and energy savings. Often, energy efficiency and energy conservation are used interchangeably in the context of lighting. However, energy conservation is defined as reduced energy use through lower quality of services [24]. Accordingly, energy conservation or energy savings include lowering of services, consumption, and standards to save energy and money by doing without [24]. For example, saving energy by a dimming schedule. Energy efficiency refers to the amount of output (e.g., in performance, service, goods, or energy) that can be produced with a given unit of energy and can be defined as the ratio of energy services to the energy input [24,47]. For example, luminous efficiency. Consequently, an efficient use of energy is to maximize the output for a given energy input. Apart from resulting in lowered energy consumption, investments in energy efficiency can also result in multiple benefits, for example, macroeconomic development, energy prices, energy security, environmental sustainability, and disposable income [48].

In the sustainability indicator framework, energy efficiency is included as a subsection within the environmental dimension and consists of six variables and several indicators. The following variables were included: (I) energy efficiency based on energy and light per km road, (II) mesopic design or adaptations (to human needs) of the spectral power distribution of the light source (to human needs), (III) light loss factor and lamp lumen depreciation, (IV) reduced energy consumption by controlled dimming, (V) direct and indirect rebound effects, and (VI) adaptations of illuminance in accordance with the surface luminance [18].

In this paper, an updated list of energy performance variables, aspects and indicators for exterior lighting are presented, and the variables have also been classified as system-wide, energy efficient, or energy conserving. Rebound effects are classified as system-wide effects, while energy efficiency and mesopic design are classified as energy efficient displayed in Table 2. The variables light loss factor and lamp lumen depreciation, controlled dimming or adaptive/smart/dynamic systems, and surface luminance are classified as energy conserving shown in Table 2.

In the European standard EN 13201-5, "Road lighting—Part 5: Energy performance indicators", two indicators are identified for calculating energy performance of road lighting, i.e., the power density indicator (PDI) and the annual energy consumption indicator (AECI) [49], and are included as energy efficient indicators in Table 2. Energy performance in PDI is expressed as the consumed electrical system power for the maintained average horizontal illuminance per square meter of the subarea to be lit ($W/(lx\cdot m^2)$). AECI is the annual energy consumption for a road lighting installation ($Wh\cdot m^{-2}$). There are also several other kinds of energy performance indicators available, e.g., the lighting system energy efficiency indicator (IPEI) and the luminaire energy efficiency indicator (IPEA) [50]. These were mainly used before the establishment of the EN 13201-5 and will therefore not be described in further detail.

Additionally, luminous efficacy (lm/W) and luminous efficiency (increased energy to light output compared to total, in percentage) are both energy efficiency variables that are included to cover future technological developments. New technologies or improvements enable the use of light sources with higher energy efficiency, but were not included in the previous sustainability framework since the focus was on LED and SSL, which already have high luminous efficiency in comparison with many older light sources.

New legislation or regulations may result in restrictions of the use of inefficient light sources or restrictions in spatial or temporal light distribution (for example restrictions concerning obtrusive light or curfews). Approval of new legislation or regulations can result in both improved energy efficiency of light sources, as has been shown by the implementation in Europe through the directive of ecodesign of energy-related products (ErP) [51], and with energy conserving by, for example, adopting the principle of "as low as reasonably achievable" (ALARA), as is recommended in the revised version of the EU green public procurement criteria for road lighting and traffic signals [52]. Another example is the possibility of using an energy efficiency labeling of the whole road lighting system that is used in some countries, such as Spain and the Netherlands, which enables assessment of the energy efficiency against stated goals [53]. Similarly, different kinds of improvements and optimizations of lighting design can also lead to either energy efficiency or energy conservation, depending on which aspect is improved. In fact, the lighting designer has a high degree of freedom to adapt the local lighting installation to fulfill identified functional needs while simultaneously maximizing energy efficiency and reducing energy consumption.

In total, this paper suggests 17 indicators for energy efficiency and energy savings (hereafter called energy performance) of exterior lighting as shown in Table 2. However, since optimized lighting design and legislation and regulations are diverse variables, it is likely that there exist additional indicators that have hitherto not been identified.

Table 2. Energy performance variables, aspects, indicators, and type. Energy performance is classified as system-wide (system), energy efficient, or energy conserving variables.

Energy Performance Variables	Aspect	Indicator	Type
Energy consumption in an area	Energy consumption for an area	Number of luminaires/area New luminaires in non-lit areas	System System
Rebound effects	Predicted energy savings will be underestimated	Percentage (rebound effect)	System
Energy efficiency	Energy efficiency based on energy and light per km road (per year)	W/lx per km road $W/(cd \cdot m^2)$ per km road	Energy efficient
Energy performance indicators in accordance with EN 13201-5	Annual energy consumption indicator (AECI)	$Wh \cdot m^{-2}$	Energy efficient
	Power Density Indicator (PDI)	$W/(lx \cdot m^2)$	Energy efficient
Luminous efficacy	Increase energy to light output	lm/W	Energy efficient
Luminous efficiency	Increase energy to light output compared to 100%	%	Energy efficient
Mesopic design or spectral distribution of the light source	Maximize visual performance and energy savings	S/P ratio	Energy efficient
		Correlated color temperature, degrees Kelvin (K)	Energy efficient
Light loss factor and lamp lumen depreciation	Minimize energy waste in the design and use stages (by accurate values of LLF or LLD)	Light loss factor (LLF), lamp lumen depreciation (LLD) or maintenance factor constant light output (CLO)	Energy conserving Energy conserving
Controlled dimming or adaptive/smart/dynamic systems	Energy savings in accordance with demand or schedule	Percentage savings (kWh/year)	Energy conserving
Surface luminance	Energy savings through increased luminance by changing the surface characteristics or adapting light levels to changed surface conditions	Percentage savings (kWh/year) due to intelligent lighting compensation for surface characteristics	Energy conserving
Legislation or regulations	Restrict the use of light sources, or spatial or temporal distribution of light	For example, implementing principles of "as low as reasonably achievable" (ALARA) or requirements on energy efficiency labelling	System, energy efficient or energy conserving
Optimized lighting design	Different implementations of optimization in the design process	For example, adaptation to current conditions or settings, or digital optimization	System, energy efficient or energy conserving

5. Results and Discussions

Most interactions between sustainable development and energy performance were found to be synergistic (52%(17), N = 33), with a high dominance within the dimension of ecology and environment in which they accounted for 71% (12 of 17) of the synergistic interactions as displayed in Figure 2. Trade-off interactions between sustainable development and energy performance were the second most common, with a total of 18% (6 of 33). Three trade-off interactions were found in each of the economic and social dimensions, and none in the ecological and environment dimension as presented in Figure 2. Three neutral interactions were found in the ecological and environmental dimension and one in the social dimension, representing 12% (4 of 33) of the interactions in total. As shown in Figure 2, three unknown interactions were found in the ecological and environmental dimension and two in the social dimensions (15%).

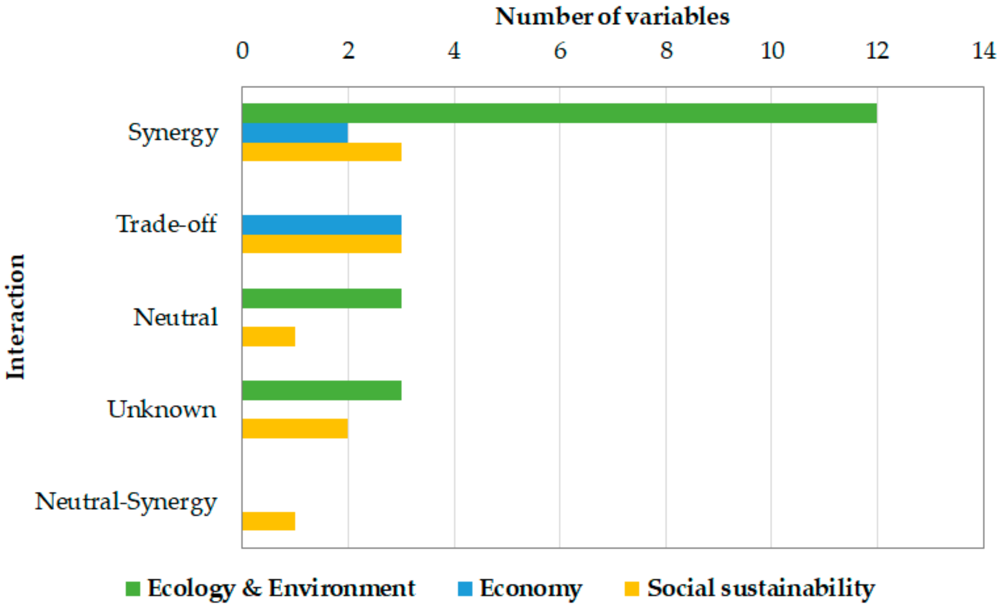

Figure 2. Interactions between sustainable development variables and energy performance divided into the three sustainability dimensions. N = 33 (Ecology & Environment N = 18; Economy N = 5; Social sustainability N = 10).

For the ecological and environmental dimension, the interactions between sustainable development and energy performance were overwhelmingly synergistic for most of the variables (12 of 18). Synergistic interactions were found between sustainable development and energy performance in the indicators: legislation/guidelines, over-illumination, minimum and maximum values, reduction of lighting during critical ecological situations, controlled lighting, luminous flux or luminous intensity per square meter, reduction of lighting in sensitive areas, number of luminaires and new luminaires in non-lit areas, indicators used for sky glow and sky brightness, hours of operation, and energy from renewable sources, as shown in Table 3. Sky glow is usually considered to be weak and mainly of relevance for astronomical light pollution, but it can result in high illuminance values (i.e. brighter than moon light) due to amplification with clouds, snow, or ground reflectance [54]. It has recently been shown that also very low light levels, (comparable to sky glow), can have an impact on circadian rhythm in some vertebrate taxa [55].

A sustainable development in the ecological and environmental dimensions often requires a decrease in the quantity or in the extent of exterior lighting to avoid or reduce ecological impacts e.g., [12,56] and light pollution [19], leading to increased energy savings by e.g., reduced energy consumption per area or increased energy efficiency (by use of, for example, more favorable light loss factors). Reductions in the hours of operation will directly increase energy savings, for example, [1].

These findings are in line with a study that showed that synergistic or positive interactions between energy goals and sustainable development goals tend to be more common [16]. This applied to both the number of interactions and their magnitude. In the 2030 Agenda, energy is addressed primarily with goal 7 (SDG7), whose overarching aim is to ensure access to affordable, reliable, sustainable and modern energy services for all. Goal 7 calls for a substantial increase in the share of renewable energy in the global energy mix and a doubling of the global rate of improvement in energy efficiency [15]. For the sustainability of exterior lighting, the relevant aim of SDG7 is improved energy efficiency because the lighting systems per se will not ensure increased access to a modern energy service, and regarding renewable energy, this mainly concerns energy needed for lighting. This shows the importance of conducting more detailed studies on specific subjects, such as exterior lighting, since a more general analysis will not cover the 17 energy indicators identified here, nor would a general analysis be able to identify all sustainability indicators for the lighting.

Energy from renewable resources decreases the use of energy from the grid, which is in line with sustainable development in terms of independent energy supplies and lessened use of non-renewable energy sources (from the grid), for example [57]. By increasing the renewable share in the total final energy consumption, the switch to renewable energy for exterior lighting will have a direct impact on target 7.2 (“By 2030, increase substantially the share of renewable energy in the global energy mix”) in the 2030 Agenda [15].

Six sustainable development variables were found to have neutral or unknown interactions with energy performance, as shown in Figure 2. It is assumed that adaptations such as lamp shielding, physical barriers, adaptations (i.e. spatial redirection), and use of optical filters do not contribute with light through reflections and do not result in a necessity to use higher wattage, which could result in higher energy consumption. Therefore, the use of lamp shielding, physical barriers, adaptations and optical filters for improving sustainable development will have a neutral interaction with energy performance. If the optical filters result in a reduction of illuminance, the interactions should be classified as a trade-off.

However, applying lamp shielding for road lighting will result in a closer spacing of the luminaires to meet the road lighting criteria and will therefore raise lighting power density and energy consumption, and increase light pollution from the light scattered after reflection from the illuminated surfaces [58]. Yet, it is uncertain if an implementation of optical filters could lead to an impact on the total life length of the luminaire (due to maintenance issues) or if there might be cases where it is necessary to use higher wattage to fulfill regulations.

Unknown interactions were found in adaptations of the spectral power distributions of light sources since there are few studies actually investigating the energy performance of light sources and wavelength adjustments (P-ratio [19], melatonin suppression index (MSI), star light index (SLI) [20]). These indices are not related to the S/P ratio (see text below on social sustainability). Falchi et al. [19] defined the P-ratio that gives the ratio of light emitted in the “protected P-band” to the light in the photopic band. The idea is that light in the protected band should be avoided, and in the original definition [19] it was light that is detrimental for stellar visibility, i.e., between 440 and 540 nm. However, MSI is based on the human melatonin suppression action spectrum, and SLI is based on scotopic spectral sensitivity [20]. The different metrics used as indicators are therefore not based on the same wavelengths in the spectral power distribution, which makes it difficult to generalize about energy performance.

Thus, it is currently challenging to simplify how energy performance will be related to adaptations towards a more sustainable development. Additionally, a new metric, the G-index, is used (voluntarily) within the European Union for setting thresholds when it is necessary for limiting the blue light content in the procurement of road lighting [52]. More specifically, the G-index is a ratio between the light below 500 nm to the total emitted luminous flux. It is recommended to use an index that can specify the spectral power distribution of interest instead of correlated color temperature since, for example, the amount of blue light is not adequately reflected in the correlated color temperature. Another option is to use a calculated index based on behavioral or visual characteristics of organisms and the lamp spectral irradiance [59]. More research in this area seems necessary to couple variations of adaptations of spectral power distributions to sustainable development and energy performance. For interactions between energy performance and the use of raw and rare materials in the LCA (especially considering LEDs), it is unknown how future changes in materials will affect energy efficiency or energy savings, as shown in Table 3. Raw and rare materials are essential elements in LED dice and color converters, but the variety of material compositions that are often used in the manufacturing process are not always included in life cycle assessments in a meticulous manner [60]. The extraction of materials is connected to SDG12, "responsible consumption and production", and more specifically, to natural resource protection, and is an important aspect to consider in the development towards a circular economy for the lighting, as is waste recycling.

For waste materials, the recycling of luminaires seems to lead to a decreased environmental impact in the LCA (including energy demand), compared to incineration or landfilling [61]. Still, it is uncertain how increased sustainability in materials and hazardous waste will impact energy consumption throughout the LCA, as displayed in Table 3. Furthermore, recycling and energy consumption in the end-of-life stage are also dependent upon recyclability, which may vary with the design of the luminaire [62,63], and with the waste management practices which may be dependent on country-specific legislation, for example [64]. Factors such as the geography that can significantly influence the interactions have been identified as context-dependencies and may relate to, for example, time, geography, governance, technology, and directionality [16].

In general, increased recycling will also lead to a reduced need for extraction of raw and rare materials and improved energy efficiency of materials production [16], which demonstrates that there are also interlinkages between the variables of sustainable development that may lead to reinforcements.

In the economic dimension, interactions between energy performance and sustainable development were either trade-offs or synergistic, which were found in three and two variables, respectively as shown in Figure 2 and Table 4.

Trade-offs with energy performance were found in the pay-back time on return of investment, economic sustainability in terms of gross domestic product (GDP) per luminaire or luminous flux per area, and in the cost benefits of savings due to the reduced number of accidents when lighting is installed as dislayed in Table 4.

Pay-back (PB) time is highly dependent on the price of the product. In particular, LED lamps and SSL technology have been shown to be associated with a higher initial cost compared to more traditional light sources despite having greater luminous efficacy, e.g., [66–68]. Eventually, however, the purchase price will decline, and the new technologies will be more competitive [66,67], and consequently have a shorter PB time compared with light sources with lower luminous efficacy. Indeed, more recent studies demonstrate that LED is a more economical beneficial alternative compared to more traditional light sources e.g., [69–71].

This shows that the PB time can be dependent on the technology and on the time-perspective of the new technology or light source. For sustainable development, it is optimal to have as short a PB time as possible while also having higher energy performance. However, since new technologies of, for example, light sources, initially generally have rather high PB time, this may lead to the continued use of less energy-efficient light sources, even though a switch to new technologies would result in less energy consumption. In this case, the interaction between sustainable development and energy performance is therefore regarded as a trade-off, but this interaction is context-dependent and may change as the price is reduced and as products improve in efficiency and quality.

Table 3. Impact and interactions between the sustainability indicators in ecology and environment dimension, and energy performance (EP) variables.

Variable	Indicator	Impact on EP Variables	Interaction
Prevent or limit new areas being lit	Establish and improve legislation, recommendations or guidelines	Will generally lead to reduced energy consumption per area. Restrictions in light inflation	Synergy
Limit the extent of illuminated areas	Lamp shielding (%)	Neutral without any other measures *. Increase energy to light output per area if shielding is used combined with reflective shields *	Neutral *
Limit the extent of illuminated areas	Eliminate over-illumination (e.g., use optimal light loss factor (LLF), lamp lumen depreciation (LLD) or maintenance factor)	Reduced energy consumption per area, AECI, PDI, percentage savings kWh/year, ALARA, optimized lighting design	Synergy
Limit the extent of illuminated areas	Follow minimum values for safety (e.g., roads)	Reduced energy consumption per area, AECI, PDI, percentage savings kWh/year, ALARA	Synergy
Limit the extent of illuminated areas	Establish maximum levels for lighting (e.g., 1 cd/m^2) equal to reduce/recommend levels of outdoor lighting for nonroads, and maximum levels of permissible illuminance or luminance for different lighting applications and their reflections	Reduced energy consumption per area, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy
Limit the duration of illumination	Reduce lighting at critical times of biological activity (migration/breeding/foraging)	Savings in energy consumption per area, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design.	Synergy
Limit the extent and duration of illumination	Controlled lighting: Shut off lights (%), dimming schedule, adaptive, smart, and intelligent lighting, sensors, innovations	Reduced energy consumption per area, savings in energy consumption per year, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy

Table 3. *Cont.*

Variable	Indicator	Impact on EP Variables	Interaction
Limit/change the intensity of light	Luminous flux or luminous intensity per square meter (or luminance)	Reduced energy consumption per area, savings in energy consumption per year, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy
Limit/change the spectral wavelength distribution of artificial light sources, and reduce blue-rich light and UV	Optical filters for wavelengths < 480 nm	Assumes that the energy consumption is the same (without a significant impact on illuminance or visibility levels)	Neutral
Limit/change the spectral wavelength distribution of artificial light sources, and reduce blue-rich light and UV	• P-ratio • Melatonin suppression index (MSI) • Star light index (SLI)	Untested	Unknown
Limit lighting in ecologically sensitive areas	Improve and change lighting to reduce the impact in sensitive areas	Reduced energy consumption per area, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy
Reduce growth of light pollution	• Number of luminaires per area • New luminaires in non-lit area	Reduced energy consumption per area	Synergy
Reduce sky glow and sky brightness	• Loss of star visibility • Number of visible stars • Visibility of the Milky Way • Measuring sky brightness ¤	Should result in lower energy consumption per area, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy
Physical barriers to stop trespassing light	• Barriers to stop trespassing light • Adaptive lighting design (spatial redirection)	Same amount of energy consumption with or without the barrier (compare with lamp shielding)	Neutral
Longer life cycle	Hours of operation during lifetime	Assuming that improved light sources are used, resulting in energy efficiency	Synergy
Renewable energy production	kWh energy from renewable energy sources	Reduced energy consumption from the grid. Reduced energy consumption per area	Synergy
Raw and rare materials	kg or kg-equivalent antimony Sb extraction impact	Unknown how future changes in materials will affect the energy performance	Unknown
Waste material	• kg (of waste product) • Hazardous waste • Recycling	Unknown how reductions or changes in various materials will impact the energy consumption.	Unknown

[*] There is an exception for road lighting since shielding may result in closer spacing of the luminaires to meet the road lighting criteria. [¤] Sky brightness can be measure by sky quality meters, or better all-sky cameras [54,65].

Table 4. Dimension, impact, and interaction between the sustainability indicators in the economic dimension and energy performance (EP) variables.

Dimension	Variable	Indicator	Impact on EP Variables	Interaction
Economy	Pay-back time	Pay-back time (PB) on return of investment	Depends on the price and light source, but new technology is often pricier and will lead to a longer pay-back time	Trade-off
Economy	Economic sustainability	• Regional GDP per luminaire • Regional GDP per luminous flux per area	Increased energy consumption per area and new luminaires in non-lit areas	Trade-off
Economy	Cost benefits and external costs	Savings due to the reduced number of accidents when additional lighting is installed	Additional lighting will result in increased energy consumption	Trade-off
Economy	Life Cycle Cost	LCC	Increased energy efficiency, AECI, PDI, optimized lighting design	Synergy
Economy	Dimming and other measures, (see controlled lighting in Table 3)	Percentage energy savings per year PB	Reduced energy consumption per area, savings in energy consumption per year, AECI, PDI, percentage savings kWh/yr, ALARA, optimized lighting design	Synergy

Economic sustainability in terms of economic health and growth is correlated with the amount of artificial lighting and the accompanying light pollution in an area. For example, globally, different levels of light pollution can be significantly explained by the real per capita GDP [6]. Similarly, more regional studies also show a correlation between lighting data and economic data [72]. Since economic growth may cause substantial increases in light pollution leading to increased energy consumption in an area [73], there is a trade-off between economic sustainability and energy usage.

Cost benefits and externalities of road lighting justify the costs of the lighting and ease economic concerns regarding sustainable development, but they are also related to human health and social well-being. The costs of the lighting include the price of the installation, operation and maintenance, and end-of-life (e.g., disposal costs), while the benefits or profitability include reduced travel time, fewer accidents, and a decrease in human fatalities and injuries [74,75]. Benefits may also include perceived safety and reduced criminality. Externalities, on the other hand, involve costs of using exterior lighting, such as obtrusive light, environmental degradation, or reduced ecosystem services due to light pollution and ecological impacts [76]. Very few scientific studies have investigated the cost benefits of exterior lighting. However, a meta-analysis of nighttime crashes that compared unlit roads with lit roads showed that road lighting is effective in reducing the number of crashes or injuries but not cost-effective as a road safety measure [75,77].

Still, current road lighting design practices are often strictly determined by standards and guidelines, for example, the European standard EN 13201 [78,79], and are motivated from the perspective that lighting is effective in increasing traffic safety or perceptions of safety. In general, areas with more traffic, a higher collision risk, or higher damage severity require greater illuminance or luminance (depending on road class), for an overview, see [80]. Savings in terms of a reduced number of accidents, fatalities, and injured humans will take place when lighting is installed or improved, leading to increased sustainability, but with an accompanying increased energy consumption. Consequently, there is a trade-off between the interactions of the cost benefits of the road lighting and the energy performance as shown in Table 4.

Synergistic interactions with energy performance were found in reduced life cycle cost (LCC) and in the percentage of energy savings per year through, for example, using dimming and other measures (see controlled lighting above).

Life cycle cost is the total cost of the product for the full lifetime, including purchase and the cost of the energy consumption in the operation and maintenance phase. Thus, if the new technology is more energy efficient, the LCC will be lower than that of a light source with lower luminous efficacy, leading to increased sustainable development in terms of both energy performance and lower costs, resulting in a synergistic interaction. However, the LCC is affected by various factors that will influence the calculations, for example, the price of energy [67] and durability [81]. If the price of energy is low, the LCC costs of new technologies with higher luminous efficacy will be higher than those of a light source with lower luminous efficacy [67].

For the percentage of energy savings per year due to, for example, dimming or reduced hours of operation, there is a synergistic interaction with energy performance in terms of increased efficiency and energy savings, as shown in Table 4.

There were numerous interactions between sustainable development and energy performance in the social dimension. Trade-off interactions were found in three variables; a neutral and a neutral-synergistic interaction were found in one variable each; synergistic interactions were found in three variables; two variables were found to have unknown interactions with energy performance, as shown in Figure 2.

Trade-offs between sustainable development and energy performance in the social dimension were identified for the number of accidents in the indicators for traffic safety design, and in illuminance as an indicator for well-being and environmental perception, as displayed in Table 5. Consistent with the interaction for cost benefits in the economic dimension, the use of road lighting will generally lead to increased traffic safety. There is empirical evidence supporting the use of road lighting compared to a non-lit road in terms of reducing the number of crashes with fatalities and the number of serious and minor injuries [77]. Likewise, improvements in lighting installations in terms of increased amounts of light indicate fewer accidents, whereas a reduction in the amount of light will increase the number of accidents with human injuries [75]. Hence, installations of road lighting on previously unlit roads or an increased amount of light results in trade-off interactions between the number of accidents and energy performance. However, the empirical evidence supporting the relationship between lighting and accidents is based on studies of which some are several decades old and may not be useful for the current conditions. Furthermore, studies of lighting and traffic safety can show highly diverse outcomes depending on how the study is performed. For example, one study has demonstrated a clear dose-response relationship between average road luminance and safety [82], while another study that analyzed over nine years of road traffic collisions concluded that there is no evidence that brighter lamps lead to improvements in traffic safety [83].

Still, designing for traffic safety means implementing the currently established standards and guidelines for road lighting that inevitably require an increased energy consumption due to the use of minimum levels of illuminance, luminance, and uniformity. There is little room, if any, for adaptations to the local design and conditions in the planning phase of road lighting that has the aim of reducing energy consumption, except for adaptive lighting systems. For example, when planning road lighting, it is difficult to incorporate light trespass or stray light originating from buildings, windows, signs, or other kinds of unwanted light that causes reflection from surfaces. Despite the fact that the trespassing light and reflections may be substantial, they can lead to a lighting design that is well above the minimum standardized levels, resulting in wasted energy. This was demonstrated with an evaluation of LED road lighting performance that clearly showed that many installations had luminance or uniformity levels above the guidelines [1], for example, in roads situated in town centers or close to buildings with lighting specifically designed for increased perceptions of safety, such as parking garages.

Recently, however, the basis of luminance and illuminance recommendations for road lighting has been questioned [80]. For road lighting that has high costs and consumes high amounts of energy, the use is mainly motivated from the perspective of increased traffic safety and human health. Thus, adjustments in the standards and regulations toward an improved equilibrium between the costs and benefits (in terms of saved human lives and reduced injuries) would be beneficial in the long run for the sustainable development and a decreased environmental impact of exterior lighting. A revision of the standards and guidelines may lead to increased sustainable development in terms of a better balance between benefits and negative consequences, such as wasted energy and various environmental impacts. In fact, the revision of the EU green public procurement criteria for road lighting and traffic signals recommends the use of the principle ALARA when selecting road classes at any moment of time to reduce light pollution, and it is also pointed out that the current lighting levels in EN13201-2 [79] are considered very high by many stakeholders [52].

A synergistic interaction was found between energy performance and design for outdoor well-being for the indicators used for correlated color temperature (S/P ratio, and degrees Kelvin). The correlated color temperature depends on the light source in use [84], and the characteristics of the correlated color temperature that is relevant for human vision at night can be estimated by the S/P ratio (scotopic/photopic ratio). The S/P ratio of the light source will, for example, affect the reassurance of pedestrians where a high S/P ratio is more beneficial, and obstacle detection in high S/P ratio areas will improve when the minimum horizontal illuminance is below 1.0 lux [85]. Light sources with better color rendering will improve the ability to see contrasts [74]. Mesopic design has been presented and evaluated as a way of adapting the light sources' spectral power distribution to better suit human vision in the mesopic range (i.e., between 0.005-5 cd/m^2) [42]. In general, light sources with higher S/P ratios are a better light source in terms of mesopic design. Mesopic design will result in energy savings in terms of higher energy efficiency [42,86], and therefore will have a synergistic interaction with energy performance. However, whether the use of a lower photopic illuminance leads to lower energy consumption may also depend on several other parameters [46]. Regarding S/P ratio and correlated color temperature, in the context of this article, it is assumed that technological improvements that result in higher visibility will, in general, also be accompanied by higher energy efficiency.

Table 5. Dimension, impact and interaction between the sustainability indicators in the social dimension and energy performance (EP) variables.

Dimension	Variable	Indicator	Impact on EP variables	Interaction
Social	Traffic safety	Number of traffic accidents	Can lead to increased energy consumption if improvements are necessary (new lit areas, increased illumination, etc.)	Trade-off
Social	Design for traffic safety	• Luminance • Illuminance • Uniformity	Often leads to new luminaires, increased wattage, or overuse of amount of lighting due to minimum requirements. Increased uniformity usually requires higher energy consumption (or an adapted light distribution).	Trade-off
Social	Design for traffic safety and well-being, environmental perception	• S/P ratio • Correlated color temperature (degrees Kelvin)	Depends on the light source, but a mesopic design should lead to energy savings	Synergistic
Social	Glare reduction for improvements of traffic safety and environmental perception	• Glare index (GR) • Threshold increment (TI) or veiling luminance • Reduce glare from nonroad lighting • De Boer scale rating survey	Depends on measures used to reduce glare	Neutral to Synergy
Social	Nonvisual effects of light	Melatonin suppression index (MSI)	Untested	Unknown
Social	Nonvisual effects of light	• Luminous flux/area • Questionnaire (sleep)	Reduced energy consumption in an area (if reducing lm/area)	Synergy
Social	Criminality	Number of crimes in an area	Can lead to increased energy consumption if improvements are necessary (new lit areas, increased illumination, etc.)	Neutral
Social	Well-being, environmental perception	Perceived outdoor lighting quality (POLQ) questionnaire	Validation is missing	Unknown
Social	Well-being, environmental perception	Illuminance (lux)	Can lead to increased energy consumption if improvements are necessary (new lit areas, increased illumination, etc.)	Trade-off
Social	Well-being, equitability (social justice)	Investments to replace old lighting systems irrespective of location	Investments in more energy-efficient lighting and new light sources: lower energy consumption in an area, energy efficiency	Synergy

For glare, there are several indicators available, for example, threshold increment TI, with the purpose of glare restriction and control of obtrusive light [79]. As mentioned previously, it is assumed that the use of lamp shielding will not result in a higher energy consumption and there is therefore a neutral interaction between shielding and energy performance. Regarding glare indicators that are used in standards and guidelines to limit the amount of glare, it is assumed that they will result in reduced amounts of lighting and therefore have a synergistic interaction with energy performance. A technological possibility is also to control the lighting distribution better and thereby reduce the amount of glare in certain directions, which would also result in a neutral interaction with energy performance or a synergistic interaction if energy consumption is reduced. Thus, the interactions identified between glare and energy performance are neutral or synergistic. However, for the De Boer scale rating, which measures perceptions of glare for laypersons, results may be somewhat subjective and measures for improvements may also vary, making it difficult to predict possible interactions between glare and energy.

The sustainable development of the nonvisual effects of light (measured by the indicator melatonin suppression index, MSI) was determined to have an unknown interaction with energy performance as shown in Table 5. This is explained above in more detail together with other indicators for changing the spectral power distribution of the lighting.

Synergistic interactions with energy performance were found in the indicators for nonvisual effects of light and with investments to replace old lighting systems, as displayed in Table 5. This is because a sustainable development for the nonvisual effects of exterior lighting involves reductions in light to avoid unwanted impacts on human health, such as the alteration of circadian rhythms [87]. Although there might be occasions where an alertness is beneficial and even wanted [5,88], the lighting design must be carefully considered and avoid unwanted light as a general effect.

For social sustainability in terms of increased equitability, for example, between socially diverse neighborhoods and through investments to replace old lighting systems, there is a synergistic interaction with energy performance, given that new lighting is more energy efficient and results in energy savings. However, the exterior lighting can be used to enhance different values in a beneficial and attractive design, but it can also be planned as a single-sided approach to solve the problem mainly with more light in a purely technical way, and consequently, this approach is most often used for when focusing on order, safety, and policing, problems that can result from urban inequalities e.g., [89].

Regarding criminality and exterior lighting, the number of crimes can be used as an indicator, and while improvements in lighting can lead to increased energy consumption or an increased number of luminaires, there is no established empirical evidence between, for example, the amount or quality of light and the number of crimes. Boyce's [5] recent overview of the benefits of light at night reviewed the relationships between lighting and the incidence of crime. He has suggested that the impact of lighting on crime is not direct but interlinked, as light helps people identify the intentions of others and enhances community confidence and the degree of social control [5]. Despite this, fear of crime (or actual crime rates) is often used as a motivation for improvements in lighting, for example by community associations, but may result in increased energy consumption. Even so, measures for lighting improvements should, in general, not lead to trade-offs between criminality and energy performance if the latest and most energy-efficient technologies are used. The interaction between criminality and energy performance was therefore determined to be neutral.

For the variable environmental perception, which is used synonymously with well-being in the outdoor environment, two different indicators can be used. One is POLQ (perceived outdoor lighting quality), which is an observer-based environmental assessment tool that has been suggested as it can be used as a questionnaire by laypersons to evaluate outdoor lighting [90]. The other suggested indicator is illuminance, which is a standardized unit used to measure and evaluate light.

Regarding POLQ, it seems to be rather straightforward to use, in theory. It is recommended to be used as a complementary tool to photometric parameters for a sustainable lighting design. The results in POLQ are divided into two major groups: the perceived strength quality (PSQ), which captures brightness perception and the direction of light, and the perceived comfort quality (PCQ), which captures aspects such as how the light is perceived in terms of "soft, natural, warm, mild, and shaded" [90]. PSQ has been shown to be significantly correlated with illuminance, color rendering, and color temperature. The POLQ scale was developed in 2014 and has not yet been fully validated [91], which is a requirement to be able to analyze the interactions in this study. Hence, the interaction between POLQ and energy performance has been determined as currently unknown.

Illuminance is a crucial factor in lighting design, and while standards and guidelines stipulate the recommended minimum levels e.g., [79], empirical evidence for optimal levels for various requirements or tasks, often seems to be missing. For example, optimal levels have only recently been suggested for improved reassurance, obstacle detection, and driver visibility of pedestrians [85]. From a broader perspective, the purpose of using artificial light is to allow human sight to function in the absence of natural light, allowing us to be as active as when we are under daylight conditions. As an indirect consequence, there seems to be no upper limit of the amount of light that humans consider necessary to use. For example, despite large historical gains in energy efficiency during the past three centuries, increased luminous efficacy is leading to an increased demand for energy for lighting [25,26]. The use of exterior light continues to increase worldwide and light pollution has likewise increased at considerable rates [7,8,92]. While some countries, e.g., France, have implemented strict laws to reduce and counteract light pollution [93], most countries lack regulations for addressing over-illumination.

Illuminance is an important indicator for social well-being, but there are currently few guidelines or standards to curb light pollution or over-illuminations. The lack of regulations that cap over-illumination together with the lack of optimal criteria for illuminance levels results in excessive and unnecessary use of energy due to the belief that it is beneficial for human well-being, while simultaneously causing negative side effects for sustainable development. Hence, there is currently a trade-off interaction between illuminance and energy performance. The negative interaction can probably be counteracted by the use of optimal criteria for illuminance levels for different purposes, restrictions on the use of light at different times, and by developing guidelines and standards to restrict light pollution.

This review did not specifically analyze interactions between the sustainability dimensions or among indicators, although areas of activity for the indicators were briefly assessed and are reported in Tables A1 and A2. However, there are probably many such interactions, and they will be important in the decision-making process. For example, a strict focus on the benefits of light at night for humans without any restrictions risks creating lighting installations that cause far-reaching light pollution, ecological impacts and obtrusive light, which runs counter to sustainable development in the environmental dimension. It is important for future studies to map the trade-offs between indicators in different dimensions, such as the use of mesopic design for humans, which results in an increase in the amount of blue light, thereby causing larger ecological impacts.

It is also of interest to develop sustainability indicators in areas where they are currently lacking and in areas where it is unknown whether a sustainable developmental direction will lead to higher or lower energy performance. Such areas are identified in this review and include, for example, the recycling of waste materials and the relationship of sustainability indicators with energy consumption.

6. Conclusions

Most interactions between sustainable development and energy performance were found to be synergistic, with a high dominance within the dimension of ecology and environment that accounted for 71% of the synergistic interactions. This review shows that environmental and ecological sustainability goes hand in hand with energy efficiency and savings. This is explained by the fact that sustainable development in these indicators aims to decrease the amount or extent of light at night, e.g., by reducing night brightness to limit light pollution. When synergistic interactions were identified in the economic and social sustainability dimensions, it was often correlated to improvements that follow energy performance, such as technologically improved light sources or new technologies.

It was determined that there exist context-dependencies for some of the interactions, e.g., the pay-back time is dependent upon the time passed since the introduction of the new technologies. Context-dependence was also found for sustainable development variables related to LCA and LCC, since recycling, waste management, and the end-of-life stage are often regulated by national or regional legislation and rules.

Applying a single-sided approach in the lighting design seems to induce trade-off interactions between sustainable development and energy performance. For example, a strict approach of implementing guidelines or standards for the purpose of traffic safety results in lighting installations that do not consider the user's actual needs for optimal function, and risks wasting energy due to over-illumination. Applying single-sided approaches in the lighting design will neglect adaptations to the local, social or environmental conditions.

To conclude, the interactions between sustainable development and energy performance can be used to establish more efficient policies for decision-making processes regarding exterior lighting. Policies should be highly prioritized toward goals that increase energy efficiency and savings, while supporting the objective of sustainable development.

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Appendix A

Table A1. Indicators and variables of sustainable development in the ecological and environmental dimension and area of activity.

Variable	Indicator	Area of Activity
Prevent or limit new areas being lit	Establish and improve legislation, recommendations or guidelines	Ecological impact, light pollution, social
Limit the extent of illuminated areas	Lamp shielding (%)	Ecological impact, light pollution, traffic safety (due to glare), social well-being
Limit the extent of illuminated areas	Eliminate over-illumination (e.g., use optimal light loss factor (LLF), lamp lumen depreciation (LLD) or maintenance factor)	Ecological impact, light pollution, LCA (CO_2), economy, traffic safety (possibly glare), social well-being
Limit the extent of illuminated areas	Follow minimum values for safety (e.g., roads)	Ecological impact, light pollution, traffic safety
Limit the extent of illuminated areas	Establish maximum levels for lighting (e.g., 1 cd/m^2) equal to reduce/recommend levels of outdoor lighting for nonroads, and maximum levels of permissible illuminance or luminance for different lighting applications and their reflection	Ecological impact, light pollution, LCA (CO_2), economy
Limit the duration of illumination	Reduce lighting at critical times of biological activity (migration/ breeding/foraging)	Ecological impact
Limit the extent and duration of illumination	Controlled lighting: Shut off lights (%), dimming schedule, adaptive, smart and intelligent lighting, sensors, innovations	Ecological impact, light pollution, LCA (CO_2), economy, traffic safety, health, social well-being
Limit/change the intensity of light	Luminous flux or luminous intensity per square meter (or luminance)	Ecological impact, light pollution, LCA (CO_2), economy, traffic safety, health, social well-being, environmental perception, POLQ questionnaire
Limit/change the spectral wavelength distribution of artificial light sources, and reduce blue-rich light and UV	Optical filters for wavelengths <480 nm	Ecological impact, light pollution, health
Limit/change the spectral wavelength distribution of artificial light sources, and reduce blue-rich light and UV	• P-ratio • Melatonin suppression index (MSI) • Star light index (SLI)	Ecological impact, light pollution, health
Limit lighting in ecologically sensitive areas	Improve and change lighting to reduce the impact in sensitive areas	Ecological impact, light pollution

Table A1. *Cont.*

Variable	Indicator	Area of Activity
Reduce growth of light pollution	• Number of luminaires per area • New luminaires in non-lit area	Ecological impact, light pollution, LCA, economy
Sky glow and sky brightness	• Loss of star visibility • Number of visible stars • Visibility of the Milky Way • Measuring sky brightness	Light pollution
Physical barriers to stop trespassing light	Barriers to stop trespassing light Adaptive lighting design	Light pollution, ecological impact, glare, traffic safety, social well-being
Longer life cycle	Hours of operation during lifetime	LCA, Economy
Renewable energy production	kWh energy from renewable energy sources	LCA
Raw and rare materials	kg or kg-equivalent antimony Sb extraction impact	LCA
Waste material	• kg (of waste product) • Hazardous waste • Recycling	LCA

Table A2. Indicators and variables of sustainable development in the economic and social dimensions and area of activity.

Dimension	Variable	Indicator	Area of Activity
Economical	Pay-back time	Pay-back time (PB) on return of investment	Economy
	Economic sustainability	• Regional GDP per luminaire • Regional GDP per luminous flux per area	Economy
	Cost benefits and external costs	Savings due to the reduced number of accidents when additional lighting is installed	Economy, traffic safety
	Life Cycle Cost	• LCC	Economy
	Dimming and other measures, see controlled lighting in Table A1)	Percentage energy savings per year PB	Ecological impact, light pollution, LCA (CO_2), economy, traffic safety, health, social well-being
Social	Traffic safety	Number of traffic accidents	Traffic safety
	Design for traffic safety	• Luminance (average cd/m^2) • Illuminance (average lux) • Uniformity	Traffic safety (regarding illuminance, see also luminous flux or luminous intensity per square meter and social well-being (environmental perception)).
	Design for traffic safety and well-being, environmental perception	• S/P ratio • Correlated color temperature (degrees Kelvin)	Traffic safety and mesopic design, social well-being, environmental perception, POLQ questionnaire.
	Glare	• Glare index (GR) • Threshold increment (TI) or veiling luminance • Reduce glare from nonroad lighting • De Boer scale rating survey	Traffic safety, social well-being, light pollution
	Nonvisual effects of light	Melatonin suppression index (MSI)	Health, Ecological impact, light pollution
	Nonvisual effects of light	• Luminous flux/area (lm/area) • Questionnaire (sleep quality)	Health, Ecological impact, light pollution (for lm/area, see also Table A1: ecological impact, light pollution, LCA (CO_2), economy, traffic safety, health, social well-being (environmental perception))
	Criminality	Number of crimes in an area	Social well-being
	Well-being, Environmental perception	POLQ questionnaire (values)	Social well-being
	Well-being, Environmental perception	Illuminance (lux)	Social well-being, traffic safety (see also Table A1 luminous flux or luminous intensity per square meter (or luminance))
	Well-being, equitability (social justice)	Investments in old lighting systems irrespective of location	Social well-being

References

1. Jägerbrand, A.K. LED (Light-Emitting Diode) Road Lighting in Practice: An Evaluation of Compliance with Regulations and Improvements for Further Energy Savings. *Energies* **2016**, *9*, 357. [CrossRef]
2. OECD; IEA. Light's Labour's Lost. Policies for Energy-Efficient Lighting. In *Support of the G8 Plan of Action*; International Energy Agency: Paris, France, 2006.
3. Fiaschi, D.; Bandinelli, R.; Conti, S. A case study for energy issues of public buildings and utilities in a small municipality: Investigation of possible improvements and integration with renewables. *Appl. Energy* **2012**, *97*, 101–114. [CrossRef]
4. Elejoste, P.; Angulo, I.; Perallos, A.; Chertudi, A.; Zuazola, I.J.G.; Moreno, A.; Azpilicueta, L.; Astrain, J.J.; Falcone, F.; Villadangos, J. An easy to deploy street light control system based on wireless communication and LED technology. *Sensors (Switzerland)* **2013**, *13*, 6492–6523. [CrossRef] [PubMed]
5. Boyce, P.R. The benefits of light at night. *Build. Environ.* **2019**, *151*, 356–367. [CrossRef]
6. Gallaway, T.; Olsen, R.N.; Mitchell, D.M. The economics of global light pollution. *Ecol. Econ.* **2010**, *69*, 658–665. [CrossRef]
7. Hölker, F.; Moss, T.; Griefahn, B.; Kloas, W.; Voigt, C.C.; Henckel, D.; Hänel, A.; Kappeler, P.M.; Völker, S.; Schwope, A.; et al. The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. *Ecol. Soc.* **2010**, *15*, 13. [CrossRef]
8. Kyba, C.C.M.; Kuester, T.; Sánchez de Miguel, A.; Baugh, K.; Jechow, A.; Hölker, F.; Bennie, J.; Elvidge, C.D.; Gaston, K.J.; Guanter, L. Artificially lit surface of Earth at night increasing in radiance and extent. *Sci. Adv.* **2017**, 3. [CrossRef] [PubMed]
9. Sánchez de Miguel, A.; Zamorano, J.; Gómez Castaño, J.; Pascual, S. Evolution of the energy consumed by street lighting in Spain estimated with DMSP-OLS data. *J. Quant. Spectrosc. Radiat. Transf.* **2014**, *139*, 109–117. [CrossRef]
10. Koen, E.L.; Minnaar, C.; Roever, C.L.; Boyles, J.G. Emerging threat of the 21st century lightscape to global biodiversity. *Glob. Chang. Biol.* **2018**, *24*, 2315–2324. [CrossRef]
11. Owens, A.C.S.; Cochard, P.; Durrant, J.; Farnworth, B.; Perkin, E.K.; Seymoure, B. Light pollution is a driver of insect declines. *Biol. Conserv.* **2020**, *241*, 108259. [CrossRef]
12. Gaston, K.J.; Davies, T.W.; Bennie, J.; Hopkins, J. Reducing the ecological consequences of night-time light pollution: Options and developments. *J. Appl. Ecol.* **2012**, *49*, 1256–1266. [CrossRef] [PubMed]
13. Lyytimäki, J. Nature's nocturnal services: Light pollution as a non-recognised challenge for ecosystem services research and management. *Ecosyst. Serv.* **2013**, *3*, e44–e48. [CrossRef]
14. Doulos, L.T.; Sioutis, I.; Kontaxis, P.; Zissis, G.; Faidas, K. A decision support system for assessment of street lighting tenders based on energy performance indicators and environmental criteria: Overview, methodology and case study. *Sustain. Cities Soc.* **2019**, 51. [CrossRef]
15. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1*; UN General Assembly: New York, NY, USA, 2015.
16. McCollum, D.L.; Echeverri, L.G.; Busch, S.; Pachauri, S.; Parkinson, S.; Rogelj, J.; Krey, V.; Minx, J.C.; Nilsson, M.; Stevance, A.S.; et al. Connecting the sustainable development goals by their energy inter-linkages. *Environ. Res. Lett.* **2018**, 13. [CrossRef]
17. Fuso Nerini, F.; Tomei, J.; To, L.S.; Bisaga, I.; Parikh, P.; Black, M.; Borrion, A.; Spataru, C.; Castán Broto, V.; Anandarajah, G.; et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* **2018**, *3*, 10–15. [CrossRef]
18. Jägerbrand, A.K. New framework of sustainable indicators for outdoor LED (light emitting diodes) lighting and SSL (solid state lighting). *Sustainability* **2015**, *7*, 1028–1063. [CrossRef]
19. Falchi, F.; Cinzano, P.; Elvidge, C.D.; Keith, D.M.; Haim, A. Limiting the impact of light pollution on human health, environment and stellar visibility. *J. Environ. Manage.* **2011**, *92*, 2714–2722. [CrossRef]
20. Aubé, M.; Roby, J.; Kocifaj, M. Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility. *PLoS ONE* **2013**, 8. [CrossRef]
21. Schulte-Römer, N.; Meier, J.; Söding, M.; Dannemann, E. The LED Paradox: How light pollution challenges experts to reconsider sustainable lighting. *Sustainability* **2019**, *11*, 6160. [CrossRef]

22. Nilsson, M.; Chisholm, E.; Griggs, D.; Howden-Chapman, P.; McCollum, D.; Messerli, P.; Neumann, B.; Stevance, A.-S.; Visbeck, M.; Stafford-Smith, M. Mapping interactions between the sustainable development goals: Lessons learned and ways forward. *Sustain. Sci.* **2018**, *13*, 1489–1503. [CrossRef]
23. Longcore, T.; Rich, C. Ecological light pollution. *Front. Ecol. Environ.* **2004**, *2*, 191–198. [CrossRef]
24. Herring, H. Energy efficiency—A critical view. *Energy* **2006**, *31*, 10–20. [CrossRef]
25. Saunders, H.D.; Tsao, J.Y. Rebound effects for lighting. *Energy Policy* **2012**, *49*, 477–478. [CrossRef]
26. Tsao, J.Y.; Saunders, H.D.; Creighton, J.R.; Coltrin, M.E.; Simmons, J.A. Solid-state lighting: An energy-economics perspective. *J. Phys. D Appl. Phys.* **2010**, *43*, 354001. [CrossRef]
27. Djuretic, A.; Kostic, M. Actual energy savings when replacing high-pressure sodium with LED luminaires in street lighting. *Energy* **2018**, *157*, 367–378. [CrossRef]
28. Sędziwy, A.; Basiura, A.; Wojnicki, I. Roadway Lighting Retrofit: Environmental and Economic Impact of Greenhouse Gases Footprint Reduction. *Sustainability* **2018**, *10*, 3925. [CrossRef]
29. Wojnicki, I.; Ernst, S.; Kotulski, L. Economic Impact of Intelligent Dynamic Control in Urban Outdoor Lighting. *Energies* **2016**, *9*, 314. [CrossRef]
30. Juntunen, E.; Tetri, E.; Tapaninen, O.; Yrjänä, S.; Kondratyev, V.; Sitomaniemi, A.; Siirtola, H.; Sarjanoja, E.M.; Aikio, J.; Heikkinen, V. A smart LED luminaire for energy savings in pedestrian road lighting. *Lighting Res. Technol.* **2015**, *47*, 103–115. [CrossRef]
31. Ozadowicz, A.; Grela, J. Energy saving in the street lighting control system-a new approach based on the EN-15232 standard. *Energy Effic.* **2017**, *10*, 563–576. [CrossRef]
32. Djuretic, A.; Skerovic, V.; Arsic, N.; Kostic, M. Luminous flux to input power ratio, power factor and harmonics when dimming high-pressure sodium and LED luminaires used in road lighting. *Lighting Res. Technol.* **2018**, *51*, 304–323. [CrossRef]
33. Jägerbrand, A.K.; Carlson, A. *Potential for More Energy-Efficient Road and Street Lighting: Comparison between Dimming and Different Types of Light Sources*; VTI Report 722; The Swedish National Road and Transport Research Institute: Linköping, Sweden, 2011. (In Swedish)
34. Sędziwy, A.; Kotulski, L. Towards Highly Energy-Efficient Roadway Lighting. *Energies* **2016**, *9*, 263. [CrossRef]
35. Sędziwy, A. Sustainable street lighting design supported by hypergraph-based computational model. *Sustainability* **2016**, *8*, 1–13. [CrossRef]
36. Yoomak, S.; Ngaopitakkul, A. Optimisation of lighting quality and energy efficiency of LED luminaires in roadway lighting systems on different road surfaces. *Sustain. Cities Soc.* **2018**, *38*, 333–347. [CrossRef]
37. Gibbons, R.B.; Li, Y.E.; Meyer, J.E. *Assessment of the Performance of Light-Emitting Diode Roadway Lighting Technology*; VTRC 16-R6; Virginia Transportation Research Council: Charlottesville, VA, USA, 2015; pp. 1–75.
38. Van Bommel, W. Lighting quality and energy efficiency, a critical review. *Light Eng.* **2011**, *19*, 5–11.
39. Pracki, P. A proposal to classify road lighting energy efficiency. *Lighting Res. Technol.* **2011**, *43*, 271–280. [CrossRef]
40. Pracki, P.; Jägerbrand, A. Application of road lighting energy efficiency evaluation system in practice. In Proceedings of the CIE Centenary Conference "Towards a New Century of Light", Paris, France, 15–16 April 2013; pp. 1038–1043.
41. Gasparovsky, D.; Dubnicka, R.; Janiga, P.; Barcik, M. Energy performance numerical indicators of public lighting. In Proceedings of the 2014 15th International Scientific Conference on Electric Power Engineering (EPE), Brno, Czech Republic, 12–14 May 2014; pp. 641–644.
42. Ylinen, A.M.; Tähkämö, L.; Puolakka, M.; Halonen, L. Road lighting quality, energy efficiency, and mesopic design—LED street lighting case study. *LEUKOS* **2011**, *8*, 9–24. [CrossRef]
43. Sędziwy, A. A New Approach to Street Lighting Design. *LEUKOS* **2016**, *12*, 151–162. [CrossRef]
44. Gasparovsky, D. Case-studies of the assessment of energy performance of road lighting. In Proceedings of the 2016 IEEE Lighting Conference of the Visegrad Countries (Lumen V4), Karpacz, Poland, 13–16 September 2016; pp. 1–5. [CrossRef]
45. Beccali, M.; Bonomolo, M.; Ciulla, G.; Galatioto, A.; Lo Brano, V. Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). *Energy* **2015**, *92*, 394–408. [CrossRef]
46. Boyce, P.R.; Fotios, S.; Richards, M. Road lighting and energy saving. *Lighting Res. Technol.* **2009**, *41*, 245–260. [CrossRef]

47. Understanding Energy Efficiency. Available online: http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568361/EPRS_BRI(2015)568361_EN.pdf (accessed on 21 September 2019).
48. Capturing the Multiple Benefits of Energy Efficiency. Available online: https://webstore.iea.org/capturing-the-multiple-benefits-of-energy-efficiency (accessed on 9 April 2020).
49. European Committee for Standardisation (CEN). *Road Lighting—Part 5: Energy Performance Indicators*; EN 13201-5; CEN: Brussels, Belgium, 2015.
50. Leccese, F.; Salvadori, G.; Rocca, M. Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy. *Energy* **2017**, *138*, 616–628. [CrossRef]
51. Energy Efficiency: Eco-Design of Energy-Related Products. Available online: http://ec.europa.eu/energy/efficiency/ecodesign/eco_design_en.htm (accessed on 30 October 2019).
52. Donatello, S.; Rodríguez Quintero, R.; Gama Caldas, M.; Wolf, O.; Van Tichelen, P.; Van Hoof, V.; Geerken, T. *(VITO) Revision of the EU Green Public Procurement Criteria for Road Lighting and Traffic Signals*; Technical Report and Criteria Proposal; Publications Office of the European Union: Luxembourg, 2019.
53. Gutierrez-Escolar, A.; Castillo-Martinez, A.; Gomez-Pulido, J.M.; Gutierrez-Martinez, J.M.; González-Seco, E.P.D.; Stapic, Z. A review of energy efficiency label of street lighting systems. *Energy Effic.* **2017**, *10*, 265–282. [CrossRef]
54. Jechow, A.; Hölker, F. Snowglow—The amplification of skyglow by snow and clouds can exceed full moon illuminance in suburban areas. *J. Imaging* **2019**, *5*, 69. [CrossRef]
55. Grubisic, M.; Haim, A.; Bhusal, P.; Dominoni, D.M.; Gabriel, K.M.A.; Jechow, A.; Kupprat, F.; Lerner, A.; Marchant, P.; Riley, W.; et al. Light pollution, circadian photoreception, and melatonin in vertebrates. *Sustainability (Switzerland)* **2019**, *11*, 6400. [CrossRef]
56. Dick, R. Applied scotobiology in luminaire design. *Lighting Res. Technol.* **2014**, *46*, 50–66. [CrossRef]
57. Mills, E. Job creation and energy savings through a transition to modern off-grid lighting. *Energy Sustain. Dev.* **2016**, *33*, 155–166. [CrossRef]
58. Boyce, P. *Lighting for Driving: Roads, Vehicles, Signs and Signals*; CRC Press, Taylor and Francis Group: Boca Raton, FL, USA, 2009.
59. Longcore, T.; Rodríguez, A.; Witherington, B.; Penniman, J.F.; Herf, L.; Herf, M. Rapid assessment of lamp spectrum to quantify ecological effects of light at night. *J. Exp. Zool. Part A Ecol. Integr. Physiol.* **2018**, *329*, 511–521. [CrossRef] [PubMed]
60. Franz, M.; Wenzl, F.P. Critical review on life cycle inventories and environmental assessments of LED-lamps. *Crit. Rev. Environ. Sci. Technol.* **2017**, *47*, 2017–2078. [CrossRef]
61. Principi, P.; Fioretti, R. A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED)—A case study. *J. Clean. Prod.* **2014**, *83*, 96–107. [CrossRef]
62. Kumar, A.; Kuppusamy, V.K.; Holuszko, M.; Song, S.; Loschiavo, A. LED lamps waste in Canada: Generation and characterization. *Resour. Conserv. Recycl.* **2019**, *146*, 329–336. [CrossRef]
63. Hendrickson, C.T.; Matthews, D.H.; Ashe, M.; Jaramillo, P.; McMichael, F.C. Reducing environmental burdens of solid-state lighting through end-of-life design. *Environ. Res. Lett.* **2010**, *5*, 014016. [CrossRef]
64. Widmer, R.; Oswald-Krapf, H.; Sinha-Khetriwal, D.; Schnellmann, M.; Böni, H. Global perspectives on e-waste. *Environ. Impact Assess. Rev.* **2005**, *25*, 436–458. [CrossRef]
65. Hänel, A.; Posch, T.; Ribas, S.J.; Aubé, M.; Duriscoe, D.; Jechow, A.; Kollath, Z.; Lolkema, D.E.; Moore, C.; Schmidt, N.; et al. Measuring night sky brightness: Methods and challenges. *J. Quant. Spectrosc. Radiat. Transf.* **2018**, *205*, 278–290. [CrossRef]
66. De Almeida, A.; Santos, B.; Paolo, B.; Quicheron, M. Solid state lighting review—Potential and challenges in Europe. *Renew. Sustain. Energy Rev.* **2014**, *34*, 30–48. [CrossRef]
67. Tähkämö, L.; Räsänen, R.S.; Halonen, L. Life cycle cost comparison of high-pressure sodium and light-emitting diode luminaires in street lighting. *Int. J. Life Cycle Assess.* **2016**, *21*, 137–145. [CrossRef]
68. Nardelli, A.; Deuschle, E.; de Azevedo, L.D.; Pessoa, J.L.N.; Ghisi, E. Assessment of Light Emitting Diodes technology for general lighting: A critical review. *Renew. Sustain. Energy Rev.* **2016**. [CrossRef]
69. Ayaz, R.; Ozcanli, A.K.; Nakir, I.; Bhusal, P.; Unal, A. Life cycle cost analysis on M1 and M2 road class luminaires installed in Turkey. *Light Eng.* **2019**, *27*, 61–70. [CrossRef]
70. Lindawati, L.; Nugraha, N.; Mayasari, M.; Supriatna, N. Financial estimation on street lighting using LED technology. *J. Eng. Sci. Technol.* **2019**, *14*, 68–81.

71. de Souza, D.F.; da Silva, P.P.F.; Fontenele, L.F.A.; Barbosa, G.D.; de Oliveira Jesus, M. Efficiency, quality, and environmental impacts: A comparative study of residential artificial lighting. *Energy Rep.* **2019**, *5*, 409–424. [CrossRef]
72. Ji, X.; Li, X.; He, Y.; Liu, X. A simple method to improve estimates of county-level economics in China using nighttime light data and GDP growth rate. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 419. [CrossRef]
73. Falchi, F.; Furgoni, R.; Gallaway, T.A.; Rybnikova, N.A.; Portnov, B.A.; Baugh, K.; Cinzano, P.; Elvidge, C.D. Light pollution in USA and Europe: The good, the bad and the ugly. *J. Environ. Manag.* **2019**, 248. [CrossRef]
74. International Commission on Illumination. *CIE 115:2010 Lighting of Roads for Motor and Pedestrian Traffic. Publication No 115*; International Commission on Illumination: Vienna, Austria, 2010.
75. Høye, A.; Elvik, R.; Sørensen, M.; Vaa, T. The Handbook of Road Safety Measures, Norwegian (On-Line) Edition. Available online: https://tsh.toi.no/innhold.htm (accessed on 27 February 2020).
76. Gaston, K.J.; Gaston, S.; Bennie, J.; Hopkins, J. Benefits and costs of artificial nighttime lighting of the environment. *Env. Rev* **2015**, *23*, 14–23. [CrossRef]
77. Daniels, S.; Martensen, H.; Schoeters, A.; Van den Berghe, W.; Papadimitriou, E.; Ziakopoulos, A.; Kaiser, S.; Aigner-Breuss, E.; Soteropoulos, A.; Wijnen, W.; et al. A systematic cost-benefit analysis of 29 road safety measures. *Accid. Anal. Prev.* **2019**, 133. [CrossRef] [PubMed]
78. European Committee for Standardisation (CEN). *Road Lighting—Part 1: Guidelines on Selection of Lighting Classes*; EN 13201-1; CEN: Brussels, Belgium, 2014.
79. European Committee for Standardisation (CEN). *Road Lighting—Part 2: Performance Requirements*; EN 13201-2; CEN: Brussels, Belgium, 2015.
80. Fotios, S.; Gibbons, R. Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. *Lighting Res. Technol.* **2018**, *50*, 154–186. [CrossRef]
81. Richter, J.L.; Van Buskirk, R.; Dalhammar, C.; Bennich, P. Optimal durability in least life cycle cost methods: The case of LED lamps. *Energy Effic.* **2019**, *12*, 107–121. [CrossRef]
82. Jackett, M.; Frith, W. Quantifying the impact of road lighting on road safety—A New Zealand Study. *IATSS Res.* **2013**, *36*, 139–145. [CrossRef]
83. Marchant, P.; Hale, J.D.; Sadler, J.P. Does changing to brighter road lighting improve road safety? Multilevel longitudinal analysis of road traffic collision frequency during the relighting of a UK city. *J. Epidemiol. Community Health* **2020**. [CrossRef]
84. Elvidge, C.D.; Keith, D.M.; Tuttle, B.T.; Baugh, K.E. Spectral identification of lighting type and character. *Sensors* **2010**, *10*, 3961–3988. [CrossRef]
85. International Commission on Illumination. *CIE 236:2019 Lighting for Pedestrians: A Summary of Empirical Data*; Publication CIE No 236; International Commission on Illumination: Vienna, Austria, 2019.
86. M. CIE and mesopic photometry. Available online: http://files.cie.co.at/584_news92.pdf (accessed on 24 April 2020).
87. Chepesiuk, R. Missing the dark: Health effects of light pollution. *Environ. Health Perspect.* **2009**, *117*, A20–A27. [CrossRef]
88. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueiro, M.G.; Gamlin, P.D.; Lockley, S.W.; O'Hagan, J.B.; et al. Measuring and using light in the melanopsin age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef]
89. Sloane, M.; Slater, D.; Entwistle, J. *Tackling Social Inequlities in Public Lighting*; The London School of Economic and Political Science: London, UK, 2016; pp. 1–41.
90. Johansson, M.; Pedersen, E.; Maleetipwan-Mattsson, P.; Kuhn, L.; Laike, T. Perceived outdoor lighting quality (POLQ): A lighting assessment tool. *J. Environ. Psychol.* **2014**, *39*, 14–21. [CrossRef]
91. Rahm, J.; Johansson, M. Assessing the pedestrian response to urban outdoor lighting: A full-scale laboratory study. *PLoS ONE* **2018**, 13. [CrossRef] [PubMed]
92. Cinzano, P.; Falchi, F.; Elvidge, C.D. The first World Atlas of the artificial night sky brightness. *Mon. Not. R. Astron. Soc.* **2001**, *328*, 689–707. [CrossRef]
93. France Adopts National Light Pollution Policy among Most Progressive in the World. Available online: https://www.darksky.org/france-light-pollution-law-2018/ (accessed on 1 March 2019).

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