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Review

Green Tunnel Solutions: An Overview of Sustainability Trends in the Last Decade (2013–2022)

Mara Lombardi, Davide Berardi, Marta Galuppi * and Maurizio Barbieri

Department of Chemical Engineering Materials Environment (DICMA), Sapienza-University of Rome, Via Eudossiana 18, 00184 Rome, Italy

* Correspondence: marta.galuppi@uniroma1.it

Abstract: In the last decade, green solutions for road tunnels have steadily emerged in the field of engineering. The focus has been on using renewable energy sources to conserve energy and address issues of disaster risk management, territorial resilience and vulnerability, especially as these issues relate to critical infrastructures (CIs), such as roads and railways. Focusing on the equilibrium of the infrastructure through integrated system services and their external effects guarantees a better evaluation of both effects as they relate to other systems and energy consumption optimisation. To this end, a systematic literature review has been conducted herein that collects and analyses studies carried out in the last decade that relate to green energy solutions in tunnels. Upon a review of the Scopus database from 2013 to 2022, 46 conceptual and empirical studies were selected. Classifications and discussions were then developed according to the main issues identified (e.g., energy saving in road tunnels, zero-energy tunnels, renewable energy sources, tunnel safety lighting, and sustainable infrastructure). Each contribution constitutes a part of the current literature that combines the problems of tunnel safety (as represented by the energy costs of safety devices, e.g., tunnel lighting systems) with issues of renewable energy sources in tunnels. The results of this systematic review offer ideas for future directions of the 'green' vision for tunnel infrastructure. This study represents the state-of-the-art of renewable energy solutions currently present worldwide. Gaps in the literature that have yet to be addressed include how to build a green system as well as how to balance its life costs. The review supports the claim that the integration of renewable energy sources can exploit innovative solutions related to the concept of resilience.

Keywords: energy saving; green tunnel; renewable sources; road safety; sustainable infrastructure; safety tunnel lighting; systematic literature review

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1. Introduction

In recent years, the concept of energy saving, and the related use of renewable resources, has been introduced as a means to attain the Sustainable Development Goals (SDGs) of the 2030 Agenda, specifically as they relate to Objective 9.1 of Goal 9: 'Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all' [1]. When it comes to the critical infrastructure (CI) of tunnels, the concept of energy efficiency is central. Energy efficiency is accomplished by finding alternative energy sources, decreasing the amount of energy consumed and reducing cost. Moreover, SDG 7 of the 2030 Agenda sets a requirement for clean and affordable energy through an increase in the use of renewable sources to be used and made affordable for everyone. The goals proposed in the agenda are social responsibility: technical knowledge must transform all ideas contained in theoretical proposals into effective opportunities and actions [2].

The discussion about road tunnel systems is centred around the performance of integrated systems, the efficient use of energy and the use of renewable energy sources while maintaining safety standards for people and things. Tunnels are a long-life infrastructure [3,4] that is necessary for connection and mobility. These facilities are characterised by an easy conceptual design and critical problems of safety. While many studies proposed the installation of photovoltaic (PV) panels to provide energy to a tunnel, it was not clear how a PV system would react in the event of a fire. A study related to a semi-transparent photovoltaic canopy [5] demonstrates that, under steady-state aeraulic conditions, the interaction between PV panels, fire, and smoke can be managed with a top opening for ventilation near the tunnel entrance rather than near the PV canopy system.

Safety requirements, such as emergency lighting and ventilation systems, are necessary in case of emergency. For example, a lack of sufficient lighting can increase the risk of traffic accidents [6], and a loss of power can inhibit the activation of the ventilation system and threaten safety in the event of a fire. Thus, reducing energy consumption does not mean reducing safety standards or the energy supply of safety systems. The importance of guaranteeing continuity of service also involves incorporating an architectural design that supports the maintenance and can overcome system failure [7]. This implies the need to create a flexible energy supply for infrastructures. Excessive lighting in tunnels often results in a waste of electricity. Methods and technologies are suggested through the use of algorithms to enhance energy efficiency and thus reduce energy consumption in road tunnels [8,9].

Although much research has been conducted on this topic, this systematic review focuses on energy solutions discussed in scientific journals from January 2013 to August 2022. While one decade of studies can present a limited view of the state of the art, it can also represent trends in the latest innovations that have a 'green tunnel' as their goal. Past studies motivated this review with the following point of reflection: how can we apply the concepts of sustainability and energy saving to road tunnel infrastructure while ensuring safety standards?

After an introduction to the study (Section 1), Section 2 is dedicated to describing the method of the systematic review; then, a bibliometric analysis of the material is presented (Section 3), followed by the results of content analysis (Section 4). Finally, a critical discussion of the studies (Section 5) is undertaken, conclusions are drawn, and future directions (Section 6) are proposed.

2. Materials and Methods

A multidisciplinary approach to the review of the topic of sustainability was proposed by Huymajer et al. [10]. Following this approach, we proposed a systematic literature review to investigate sustainable green tunnel solutions.

The theoretical methodology adopted is the PRISMA statements described in Section 2.1. The process flow can be summarised as follows (see Figure 1):

1. **Identification** of research materials (topic, database and keywords);
2. Initial **filtering** of content (according to the purposes of the abstract);
3. **Eligibility** assessment of publications with respect to search criteria (in continuity with the research scope);
4. **Meta-analysis** of selected papers (full-text review).

2.1. Identification: Data Collection Process

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11]. PRISMA is a consolidated procedure for scientific research in the fields of energy and sustainability. A systematic review gives a summary of the state of knowledge on a topic. For this reason, the fundamental steps for the collection, analysis and categorisation were carried out following the guidelines indicated in the PRISMA checklist. The article selection process is shown in Figure 1, coherently with the PRISMA flow diagram model [12].

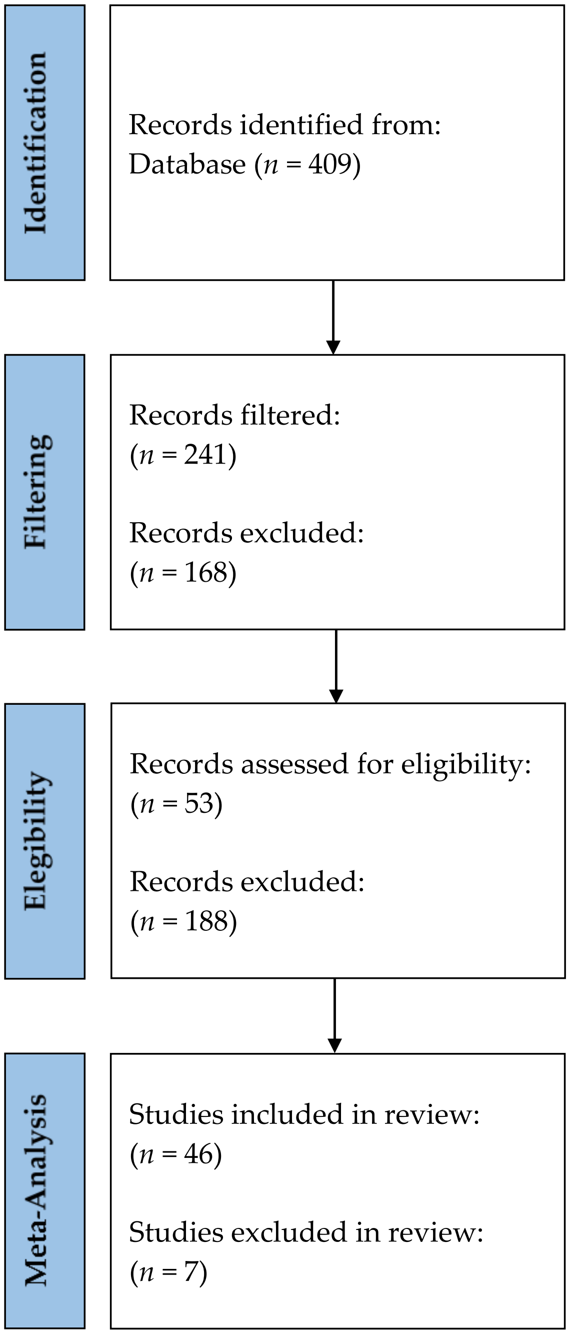

Figure 1. Flow chart of criteria for the selection of documents analysed.

In line with these guidelines, each phase of the review was performed in accordance with certain criteria, as follows:

- **Topic**: green road tunnel solutions using renewables energies;
- **Database** and time frame: Scopus, from 2013 to 2022;
- **Eligibility**: an analysis of the selected papers' abstracts to evaluate their inclusion/ exclusion in the study;
- **Classification and Categorisation**: selected articles were analysed according to the eligibility criterion and classified into 'subject topic' areas in the results section.

Further analysis of the full text of each document was then carried out to determine whether it fits the stated aim of the study.

The collection of documents includes research found in Scopus [13], a consolidated research database known for its quality and usefulness to the research community. Although its coverage includes journals more than any other means of disseminating scientific knowledge, it is sufficient for the engineering fields.

To procure a collection of publications that addressed the theme of green tunnel solutions, research was split into different subjects linked to singular keywords.

In addition to chosen keywords, a second relevant criterion concerning time frame was included. The theme of green sources in infrastructure, such as tunnels, has developed faster in the last decade not only because of continuous improvements to new technologies but also because of the demand for such change to reach the objectives of Agenda 2030 [14].

In the Scopus database, some input strings for words included in the abstract, title, or keywords of the studies were selected.

The choice of words was very detailed because the research needed to focus on the most fitting studies and exclude those with only general themes.

2.2. Filtering (Search Strategy): Formulation and Database

The research strategy involved, first, adopting a search query to input into the Scopus database. This involved selecting a basic set of words that must be present either in the title, abstract, or keywords of each study. The decision to use Scopus instead of Google Scholar or Web of Science arose from the need to choose a database that provided structured data about the publications and citations, and information about the author. Moreover, Scopus indexes more journals and covers more modern materials than other databases [10,15,16]. A collection of 409 documents were used as a starting point from which to classify input word strings, specifically query inputs (see Table 1):

- Query A: 'energy' 'saving' 'road' 'tunnel';
- Query B: 'sustainable' 'infrastructure' 'tunnel';
- Query C: 'energy' 'lighting' 'zero' 'tunnel'.

Table 1. Query inputs for research on Scopus.

STREAM	QUERY
QUERY A	TITLE-ABS-KEY ('energy' AND 'saving' AND 'road' AND 'tunnel') AND SUBJAREA (engineering AND energy) AND PUBYEAR > 2012 AND PUBYEAR < 2023
QUERY B	TITLE-ABS-KEY ('sustainable' AND 'infrastructure' AND 'tunnel') AND SUBJAREA (engineering AND energy) AND PUBYEAR > 2012 AND PUBYEAR < 2023
QUERY C	TITLE-ABS-KEY ('energy' AND 'lighting' AND 'zero' AND 'tunnel') AND SUBJAREA (engineering AND energy) AND PUBYEAR > 2012 AND PUBYEAR < 2023

The initial research resulted in 117 documents for Query A, 209 for Query B, and 3 for Query C. The next step to make the search results compliant with the scope of the study was to limit the subject area to only two fields: engineering and energy. After this filtering, 92 articles for Query A, 146 articles for Query B and 3 articles for Query C remained.

The core objective of the research was to find articles that fit the discussion topic of the review: green tunnel solutions and, specifically, aspects of their safety and sustainability.

To this end, after an initial analysis of the abstracts and contents of each paper, only 46 studies were chosen in the eligibility phase. After this phase, a meta-analysis (a deep review with the objective of categorising chosen studies according to how they fit the topic) was conducted. Results were then transferred to an Excel spreadsheet to conduct a further systematic review and to analyse data through a bibliometric tool.

Documents were selected based on a series of inclusion and exclusion criteria. These criteria, detailed in Table 2, were among the starting ones used to identify the sample of articles. First, a set of common keywords in the article group was selected. Then, the field was confined according to language, source type and time range.

Table 2. Inclusion criteria.

Inclusion Criteria	Description
Keywords	Safety tunnel lighting, renewables energy, road safety, zero energy tunnel, energy demand
Language	English
Source type	Peer-reviewed articles
Time interval	2013–2022

The topics chosen related to the sustainability of tunnels [17,18]. A detailed description of each topic (in Table 3) provided guidelines for choosing the criteria of the selected papers.

Table 3. Subject topic stream for articles.

Subject Topic	Definition
S.1 Sustainable infrastructure	Limit the negative impact of climate change.
S.2 Renewable sources	The use of renewable sources: PV, wind, etc.
S.3 Zero-energy tunnel	Minimise to near zero the use of energy; improve efficiency.
S.4 Tunnel safety lighting	Reduce the amount of energy consumed to ensure safety of the tunnel lighting system.

Finally, the research issues addressed by the selected articles were investigated. In Appendix A, the full list of documents with assigned reference numbers (according to the stream in Table 3) is reported.

2.3. Eligibility: Metrics Results

The list of 21 journals from the engineering and energy fields, matching the selected publications and arranged in alphabetical order, is summarised in Table 4 below. Based on journal rankings or impact factors found on the Scimago website [19,20], a value was assigned to each journal with respect to quartile citation and H-index.

Table 4. Journal, H-index, and Scimago quartile citation.

Journal	H-Index	Quartile Citation
Advances in Civil Engineering	33	Q2
Applied Optics	203	Q2
Applied Mechanics and Materials	37	-
Applied Sciences (Switzerland)	75	Q2
Bautechnik	19	Q3
Building and Environment	172	Q1
Building Simulation	38	Q1
Elektrische Bahnen	12	Q4
Energies	111	Q1
Frontiers in Sustainable Cities	-	-
IEEE Transactions on Industry Applications	206	Q1
IOP Conference Series: Materials Science and Engineering	48	-
Journal of Donghua University (English edition)	11	Q4
Journal of Light and Visual Environment	19	-
Modern Tunnelling Technology	15	Q3
Progress in Photovoltaics: Research and Applications	137	Q1
SAE Technical Papers	116	Q3
Sustainable Cities and Society	82	Q1
Sustainable Construction Materials and Technologies	15	-
Sustainability (Switzerland)	109	Q1
Tunnelling and Underground Space Technology	113	Q1
Tunnels and Tunnelling International	15	Q4

A systematic literature review, according to PRISMA guidelines, must reflect the queries compliant with the proposed approach (see Table 1). Therefore, the scope of this review is precisely defined, and the dataset is composed of a few elements. Thus, the topic of each article synthesising the findings of existing literature on certain research trends can be manually reviewed [21].

2.4. Meta-Analysis Statement: Full-Text Review

A set of 46 articles (the output of the eligibility phase) was ultimately reviewed. Analysis and synthesis of the data extracted from the selected papers were conducted in two phases. In Section 3, a bibliometric analysis report is presented; in Section 4, the results are discussed.

3. Bibliometrics

The bibliometric section is an instrument used for analysing results, making comparisons and underlining the evidence and gaps in the literature [22]. A content analysis according to bibliographic and network data analysis was conducted. Our research identified the main topics and their trends over time, prolific authors and the level of co-authorship among the authors [23]. Previous researchers have applied bibliometric analysis to inspect sustainability in tunnelling through an interdisciplinary vision without the use of a science map approach [10]. Other studies have performed bibliometric analyses using VOSviewer [24,25]. VOSviewer analyses the content and data of published literature imported into the software. Separate groups of text concepts are detected by performing cluster analysis. VOSviewer software allows for results to be displayed in three different ways: a network visualisation, an overlay visualisation and a density visualisation. Visualisations are based on bibliometric network distance: the distance between two nodes reflects the relation between them [25]. By exporting Scopus data in text format (.csv) and applying a bibliographic analysis of author data, the classification below was provided. Based on the collection parameters, the output showed a connection (potential author matches via density visualisation) between the most prolific authors (by the number of citations) and co-authored articles. A density visualisation map is presented in Figure 2 below. VOSviewer reads data from files input from Scopus and displays the co-authorship relation. The parameters used for the display were: a full counting method, which means that all co-occurrence has the same weight; a minimum number of documents per author equal to 1; and a minimum number of citations equal to 2. The resulting cluster showed that only 104 of a total of 150 authors met this threshold. The density visualisation has been set with the colour intensity related to the number of citations. Figure 2 illustrates that Pena Garcia, Gil Martin and Lopez are the authors with the most co-occurrences and citations.

In a systematic literature review, a bibliometric analysis is a required step of the described method. By means of an overlay network visualisation, topic mapping of Scopus data in the period from 2013 to 2022 is presented in Figure 3 below. By reading the data of a Scopus input file, VOSviewer creates network data using words included in the titles of works. With a limitation of occurrence of two times per word applied, only 19 of the 168 words met this threshold. The output of the most relevant terms is shown in Figure 3. The network visualisation detected 18 items and five clusters. Energy, tunnel lighting and lighting installation are the most selected terms; these were also the most dominant and widely discussed by researchers.

Taking account of Figures 2 and 3 together, some considerations emerge: energy, lighting systems, road tunnels, maintenance and the application of solutions are major topics of discussion. Authors that investigate green solutions for tunnels are not a large group; relevant authors are those with the most cited papers.

The next phase of the review consisted of quantifying bibliometric parameters. The figures below show the number of articles published per year, the most cited papers, country distribution, connection and topic trends. Data were elaborated upon (e.g., publication trend for the year, type of article and source list) by means of a special (open source and free) tool called the SJR tool (Scimago Journal & Country Rank) [26].

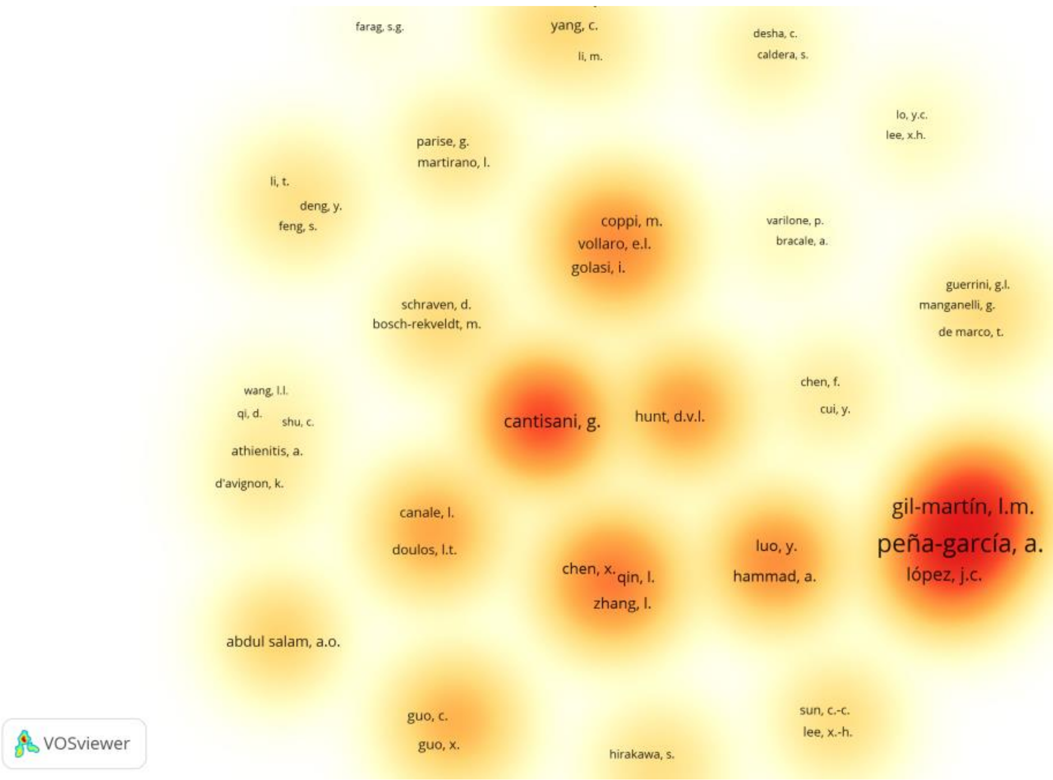

Figure 2. Density visualisation of potential author matches.

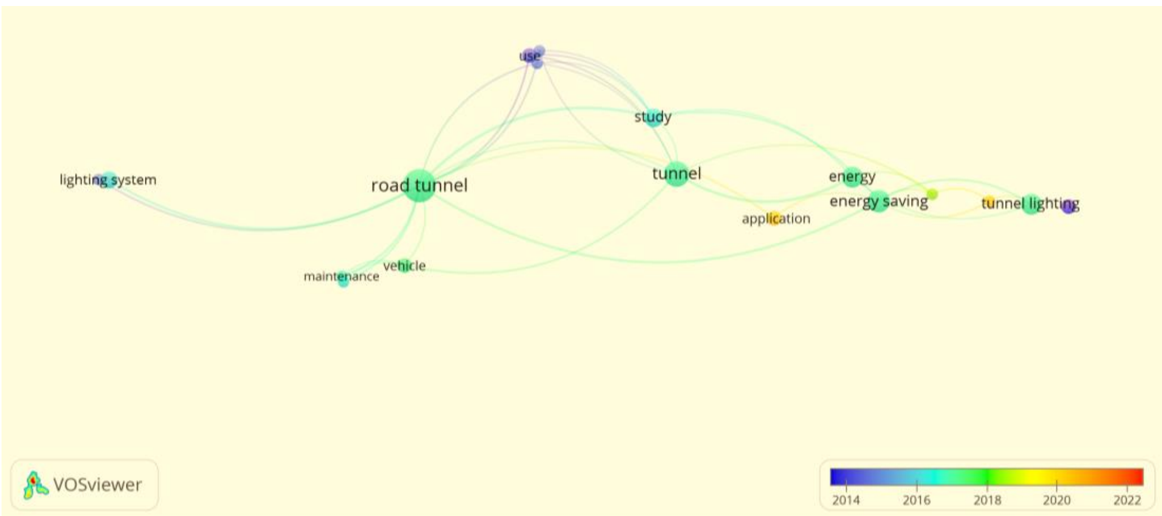

Figure 3. Mapping of most relevant terms.

The distribution of publications per year is shown in Figure 4. The trend in the number of publications for the decade from 2013 to 2022 appears constant, except for two years: 2015 and 2020. The main reason for this is the Paris Agreement of 2015. One of the major objectives of the Paris Agreement to stop climate change is regarding energy consumption and operational continuity of critical infrastructures [27].

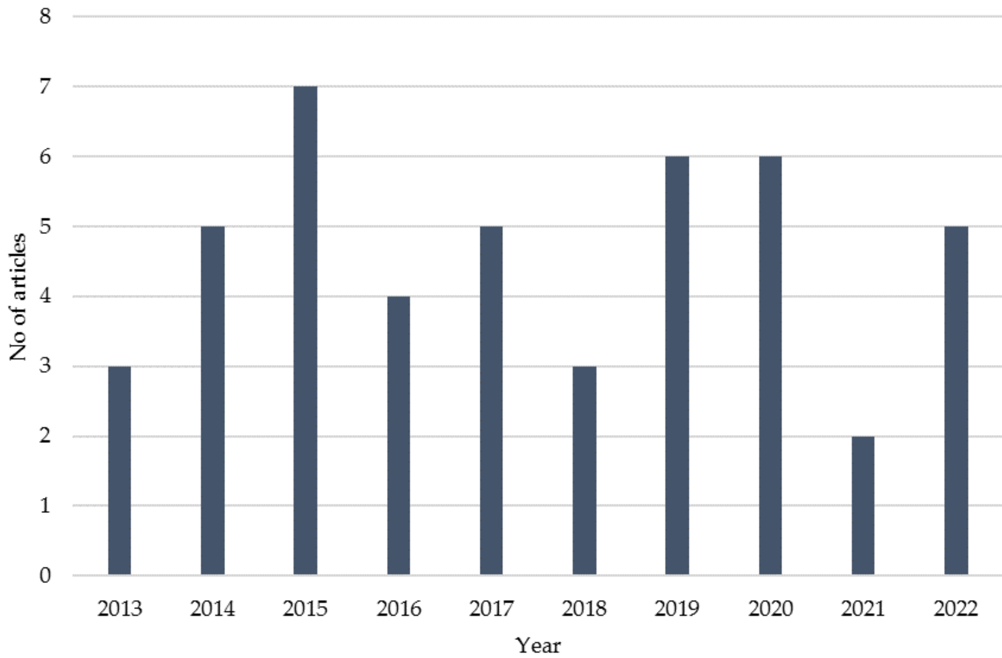

Figure 4. Number of publications per year.

The majority of the papers were published by researchers from China and Europe (mostly Spain and Italy), as shown in Figure 5 and in Table 5.

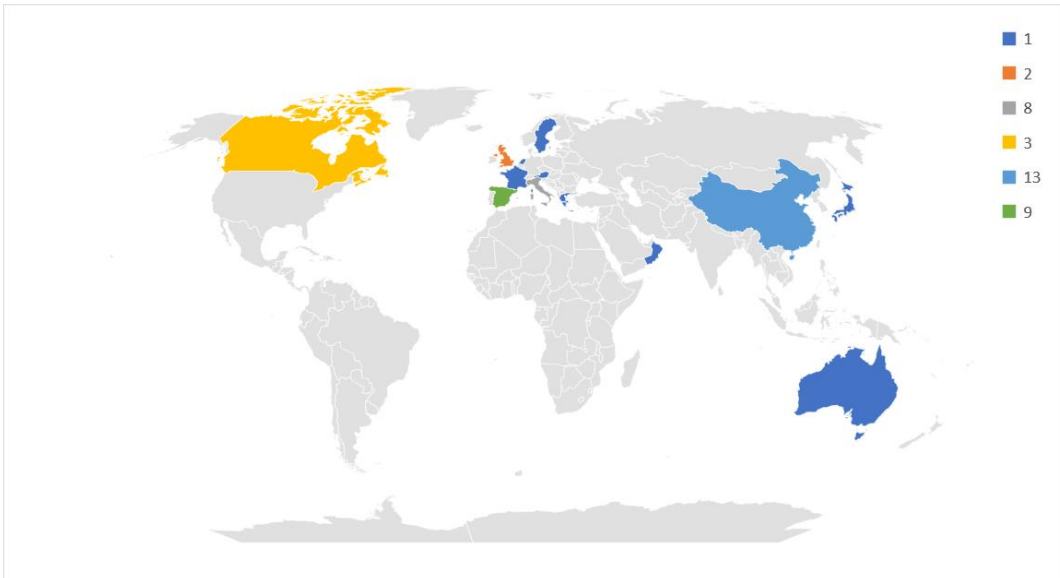

Figure 5. Graphical distribution of first author's country.

Table 5. Number of articles per country.

Country	No.
China	13
Spain	9
Italy	8
Canada	3
United Kingdom	2
France, the Netherlands, Oman, Germany, Australia, Bulgaria, Greece, Switzerland, Japan	1

The most cited articles among the collected publications are presented in Table 6 below. Due to the small number of reviewed articles (46 in total), only the top 10 most cited are included.

Table 6. Ranking of most cited papers.

Ranking	Title	Author	Journal	Country	No
1	Management of road tunnels: Construction, maintenance and lighting costs	Moretti, L., Cantisani, G. & Di Mascio, P.	Tunnelling and Underground Space Technology	Italy	77
2	Energy optimization of road tunnel lighting systems	Salata, F., Golasi, I., Bovenzi, S., Vollaro, E., Pagliaro, F., Cellucci, L., Coppi, M., Gugliermetti, F. & Vollaro, A.	Sustainability	Italy	59
3	Study of light-pipes for the use of sunlight in road tunnels: From a scale model to real tunnels	Gil-Martín, L.M., Peña-García, A., Jiménez, A. & Hernández-Montes, E.	Tunnelling and Underground Space Technology	Spain	54
4	Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants	Peña-García, A., López, J.C. & Grindlay, A.L.	Tunnelling and Underground Space Technology	Spain	41
5	Study of pergolas for energy savings in road tunnels: Comparison with tension structures	Peña-García, A. & Gil-Martín, L.M.	Tunnelling and Underground Space Technology	Spain	40
6	Use of sunlight in road tunnels: An approach to the improvement of light-pipes' efficacy through heliostats	Peña-García, A., Gil-Martín, L.M. & Hernández-Montes, E.	Tunnelling and Underground Space Technology	Spain	39
7	History and recent development of multi-purpose utility tunnels	Luo Y., Alaghbandrad A., Genger T.K. & Hammad A.	Tunnelling and Underground Space Technology	Canada	34
8	Assessment of the future resilience of sustainable urban sub-surface environments	Makana, L.O., Jefferson, I., Hunt, D.V.L. & Rogers, C.D.F.	Tunnelling and Underground Space Technology	UK	27
9	Management optimization of the luminous flux regulation of a lighting system in road tunnels	Salata, F., Golasi, I., Poliziani, A., Futia, A., De Lieto Vollaro, E., Coppi, M. & De Lieto Vollaro, A.	Sustainability	Italy	24
10	Energy saving in tunnels lighting using shading structures	Salam, A.A. & Mezher, K.	IEEE	UK	22

In Figure 6, the subdivision of documents between conference papers and journal articles is shown. The majority of documents chosen for this study are journal articles. Because of the peer-review process, journal articles are considered higher quality than conference papers; however, the chosen conference proceedings are nevertheless relevant to the topic at hand. Moreover, they come out of conferences related to the CI sector and, by extension, tunnels.

As shown in Figure 6, both articles submitted to journals or presented at conferences are related to the relevance of green energy solutions in CI.

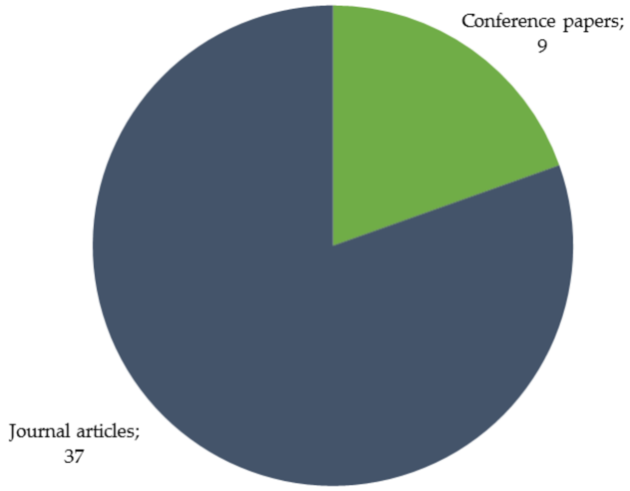

Figure 6. Graph of document type.

Another significant subdivision emerges with respect to each article's approach—either conceptual or empirical (see Figure 7). Conceptual articles include theoretical studies: data collection and analysis, literature reviews of certain topics and structured studies with a demonstration through the use of software modelling. Empirical articles are those based on experimentation, such as case studies providing a new case, experimental prototypes and experimentation on real equipment.

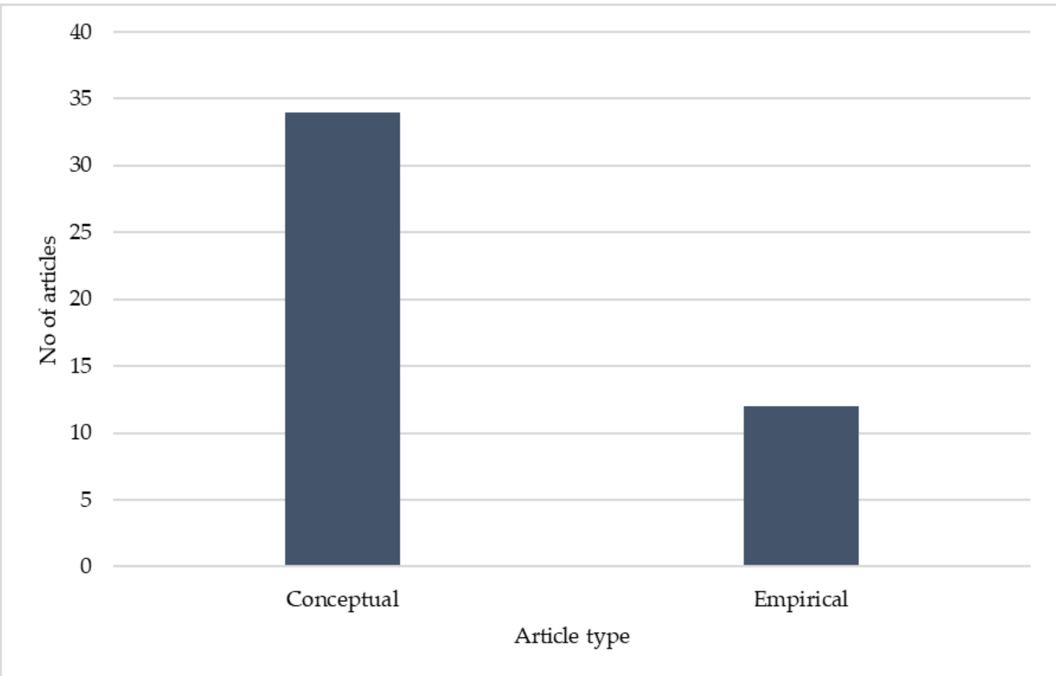

Figure 7. Number of empirical and conceptual studies.

A further classification was performed that created the following empirical sub-categories: empirical studies based on scale models and prototypes (E-P), empirical studies based on experimentation on real equipment (E-T), and empirical studies based on a newly provided case study (E-N). For conceptual works, the following sub-categories were defined: studies based on data collection and analysis (C-D), studies based on software simulation and modelling (C-M), and literature reviews (C-R).

These sub-categories (see Figure 8) refer to the target of each study and the means employed to achieve it. The designation of a category follows a logic of association in accordance with the purposes of the article and its setting.

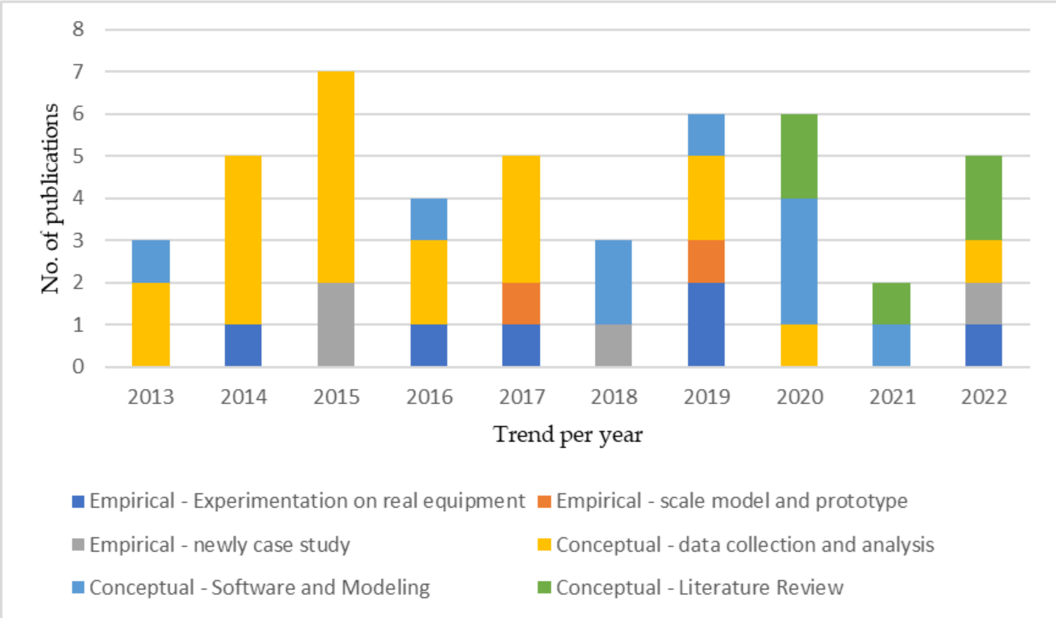

Figure 8. Sub-category trends per year.

In Table 3, the discussion topic was divided into four research trends. The number of articles screened for each subject topic is highlighted in Figure 9.

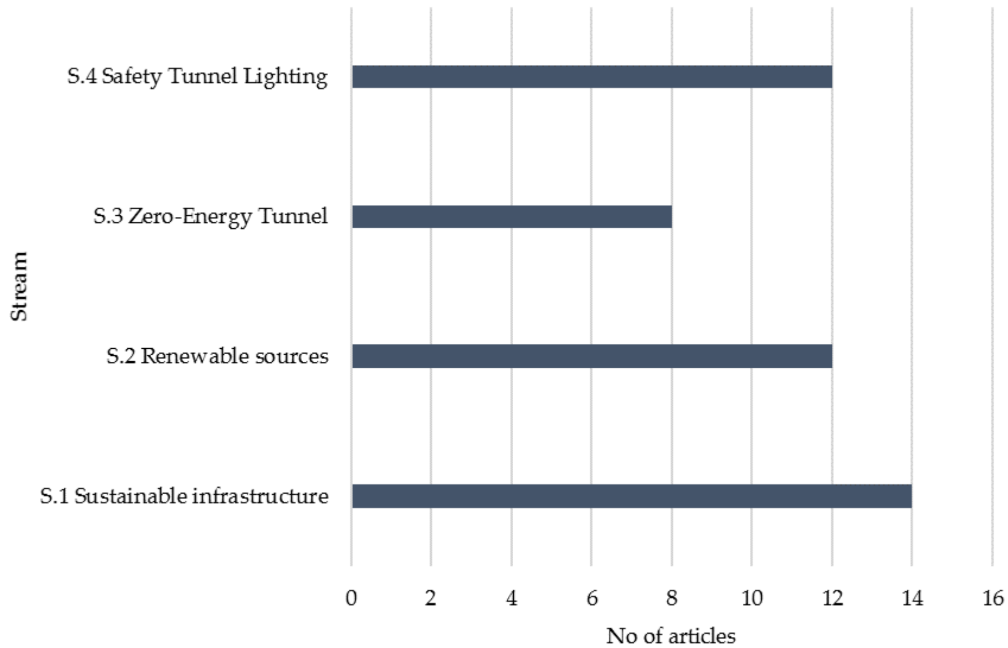

Figure 9. Number of articles per subject topic.

Merging its content and aim, a relevant reflection arises: although the number of articles for every topic is similar, each topic group accounts for a different aspect of the problem. With reference to the basic question at the beginning of this article—what does it mean when infrastructure becomes sustainable—different issues are implicated: energy consumption and optimisation, green energy sources and the safety of lighting and ventilation systems.

These issues must be analysed in order to catch the core of the isolated issues, and then the results must be verified as an integrated approach to safety and sustainability goals.

4. Results of Meta-Analysis

Based on relevant research areas consistent with the theme stated in the introduction, the results of this review are presented in four distinct sections: sustainable infrastructure, renewable energy sources, zero-energy tunnels and tunnel safety lighting.

First, a presentation of the research trends from a temporal perspective is offered in Figure 10.

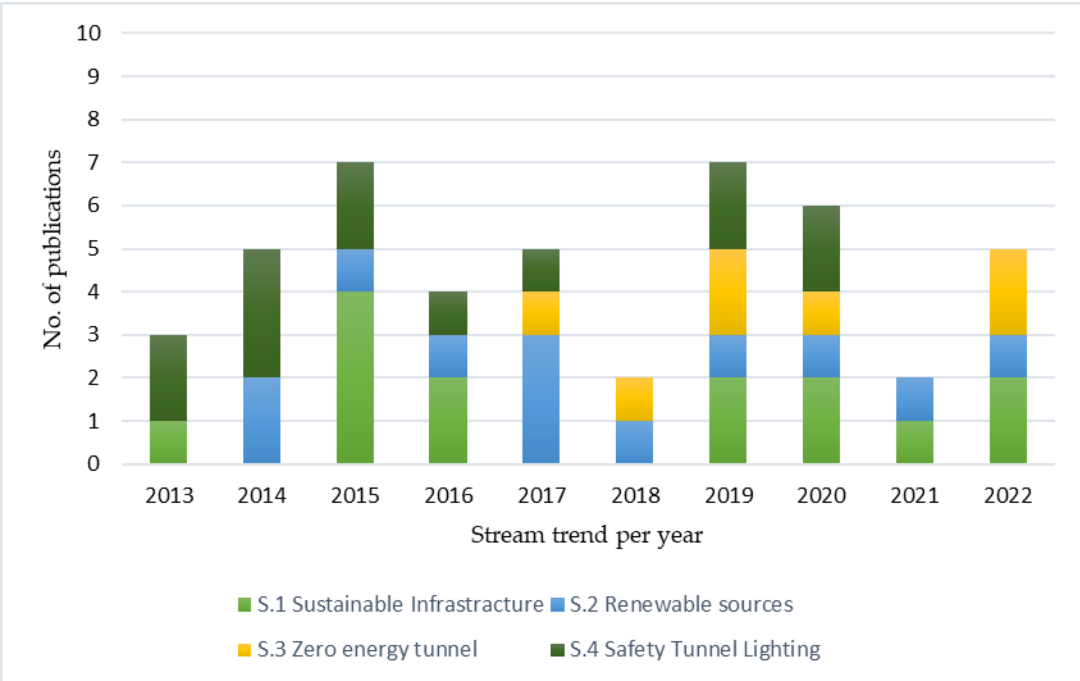

Figure 10. Research trends per year.

The distribution of the number of publications in each half of the decade in question (2013–2022) is almost equal: 24 for the years from 2013 to 2017 and 22 for the years from 2018 to 2022. The most notable results appear in 2015 and 2019, as was remarked upon in the bibliometric section (see Section 3 of that section).

4.1. Sustainable Infrastructure

Analysing what is meant by a 'sustainable road tunnel' is a complex undertaking. A multi-criterion approach to the concept of sustainability simultaneously merges environmental, economic and social considerations about the design and management of a tunnel system. When formulating strategies for tunnel design and operation, all legal requirements, technical guidelines and facilities should be taken into consideration [28]. Such an approach is not a simple undertaking; however, changes to current approaches must be made that will act on the sustainability aspects of the infrastructure and, therefore, on the issues of renewable energies, zero-energy tunnels and tunnel safety lighting.

Four main perspectives define the sustainability of a tunnel: energetic, social, resilience and transitional [17]. The social perspective refers to the social acceptance of sustainability themes. The transitional perspective expresses the challenge of transitioning to sustainable tunnels, where social commitment and involvement have an impact on the implementation of such a transition. From an energy perspective, it also is necessary to optimise energy needs in order to balance pollutant emissions generated in the operational life cycle of the tunnel system [29].

The resilience perspective is the most difficult one to address. A resilient system is capable of recovering from a dangerous external event; indeed, resilience pertains to recovery and flexibility. To this end, the use of intelligent materials is proposed [30]. Such an approach sees the integration of the concept of resilience with materials that become 'intelligent materials', combining the latter with civil engineering applications to control performance in static and dynamic conditions. With the aim of achieving sustainable infrastructure, it is necessary to develop methodologies [31] to quantify implemented solutions both spatially and temporally. New developments can only arise from very specific economic, environmental and social needs pointed out by the data, and without these data, such needs can go undetected. From an economic perspective, Bergman et al. [32] propose an analytical approach based on a sustainability dimension and an identification of the limits of a system's life cycle to develop a series of criteria that can be applied to empirical cases and real data.

Furthermore, for an economic evaluation of the life cycle of a road tunnel system, it is important to take into consideration aspects of design and construction, management costs and road surfaces [33], which can have both a technically and economically positive impact. Tunnels, therefore, become multifunctional by means of a multi-faceted risk management approach that can be exploited transversally to all tunnels of the world, guaranteeing a unique solution for resilient and sustainable development [34]. Smart technologies must become a key element of the solutions for tunnel infrastructure management; resources such as Building Information Modelling (BIM) can support the flow of information to evaluate these infrastructures dynamically [35].

Bracale et al. [36] call attention to tunnel lighting safety requirements and the need for an energy supply for tunnel safety systems. In particular, to evaluate the higher energy consumption of the lamps in a tunnel, an economic criterion for the selection of technical and technological solutions must be included. The theme of multidimensionality addressed above is taken up by Yi et al. [8] as a means of lighting system management. In fact, influencing factors and quantitative indices of the level of energy savings related to lighting are modelled using software and validated through experimental tests. Two studies [37,38] focus on the electrical systems of road tunnels, comparing the minimum technical requirements of the design of the lighting system required by law. Solutions are based on an adaptive criterion in the first study and on a practical method to estimate load demand and annual energy cost in the second, both adopting a smart control system to optimise energy balance. Salata et al. [39] demonstrate an optimisation of energy consumption by showing that, with special asphalts characterised by a high reflective coefficient, it is possible to achieve equivalent lighting with a lower luminous flux and, consequently, lower energy consumption.

4.2. Renewable Sources

The use of renewable energy sources is a central theme in the creation of sustainable infrastructures. From a theoretical perspective, renewable energy sources are those sources that are inexhaustible or renewed over time. The primary sources of alternative energy are the sun and wind. To make the most of these two resources within a tunnel system, they must be sufficiently integrated. Peña García et al. [40] focus on the use of solar energy to demonstrate that PV systems near tunnel portal gates generate savings in terms of energy, number of projectors installed, CO_2 emissions and environmental impact. The energy consumed by the lighting and ventilation systems of a tunnel system is about 80% and 20% of a tunnel's total energy consumption, respectively. Using a PV system and hybrid inverter points to the possibility of reducing the adaptive luminance of L20 by means of shading structures at the tunnel entrance [41].

Tunnel design data suggest that the key to achieving a sustainable tunnel system will involve using sunlight in a focused way. Peña García [42] proposes an experimental equation called SunLight in Tunnels (SLT) to predict and evaluate energy savings in road tunnels. Starting from the desired conditions, characteristic parameters, such as the surface area and distribution of diffusers and the number of holes or light pipes, can be calculated. A theoretical use of this equation is proposed that includes all the characteristic parameters for evaluating luminance and luminous flux to demonstrate that any solution involving the use of sunlight in road tunnels according to the two main strategies proposed to date (shift in threshold zone and light injection) can be easily evaluated and compared to other solutions. Garmarini et al. [43] apply a sensitivity analysis to the energy efficiency of a solar prototype vehicle. Furthermore, Zhao et al. [44] propose an energy-saving solution with an algorithm based on a long short-term memory neural network using the least squares method to define luminance and a reduction coefficient for any speed and traffic flow conditions. Other papers [45,46] offer an experimental approach, such as a system that utilises a coupled heliostat-light pipe system for solar light collection as a sunlight source. In another case study [47], the same author experiments with how changes in vegetation around the portal gate (e.g., the use of common ivy) in an alpine environment can help the lighting system save energy and thus guarantee the sustainability of the road tunnel. The solutions proposed above are collected in a review [48] that highlights that the tasks of renewable resources can be performed through different systems, e.g., optimisation of an already existing LED system by simulations and models [49], the use of vegetation to decrease energy demand [50] or, simply, a better design of already existing resources [51]. The aim of the zero-energy tunnel, which includes the use of the renewable energy sources presented above, is illustrated below.

4.3. Zero-Energy Tunnel

The concept of the ‘zero-energy tunnel’ must be understood in an idealistic way. With the current state-of-the-art knowledge, there is no evidence to demonstrate a balance of zero energy. The vision of ‘zero’ represents the arrival point for integrating safety and sustainability in road tunnels.

Doulos et al. [52] attempt to develop this vision of zero through the use of technological resources, such as the Supervisory Control and Data Acquisition (SCADA) system. This allows one to remotely program the influencing lighting system factor, how weather, traffic and stopping distance, to design according to updated conditions. In another theoretical approach, Yang et al. [53] propose a method using self-developed software based on a point-by-point algorithm to evaluate the influence of the angles of luminaires and installation modes on the road tunnel. Other examples of near-zero-energy achievement exploit meteorological conditions [54] (e.g., wind, directionality) or investigate a reasonable time factor for CO-based emissions [55] to optimise ventilation systems.

Looking towards the goal of a zero-energy tunnel, one paper simulates the interaction between a fire and a tunnel PV system [5]. Another [56] studies the integration of semi-transparent PV cells into sunscreen structures installed above a portal tunnel to reduce tunnel lighting requirements and counteract energy consumption in critical time slots through the use of simulation software. Such a study allows for an understanding of the quantitative energy impact of the proposed solution. Jiang et al. [57] propose a zero-energy system in which a sliding plate absorbs the kinetic energy produced by decelerating vehicles. The absorbed energy is then converted into electrical energy.

4.4. Tunnel Safety Lighting

The number of researchers who include issues of tunnel safety lighting in their work is considerable. The reasons are as follows: a tunnel is a confined environment and requires a safety system design that guarantees user safety and infrastructure performance. In the context of proposed green solutions, the optimisation of a lighting system’s energy consumption is of utmost importance. This section will present articles that illustrate solutions aimed at achieving sustainable tunnels while considering safety aspects. Concerning the topic of lighting optimisation, a study led by Yang et al. [58] proposes a methodology (known as high-performance uniformity) that, by exploiting LED lamps, ensures lighting uniformity, greater user safety and a saving of 20% compared to ordinary solutions. Tsai et al. [59] comparatively address the same issue by proposing a solution that employs a free lens with a cluster of light-emitting diodes. This system makes it possible to reduce dazzle and increase safety. Other authors [60] propose a comparison of the use of pergolas and tension structures through an equation that exploits the structural characteristics of a tunnel to reduce energy consumption. On the same subject, Salam et al. [61] adopt shading structures to achieve great reductions in tunnel lighting requirements by reducing artificial lighting intensities at entrances and exits. Other energy solutions take advantage of tunnel cross-sections [62]; under energetic and financial considerations, it becomes reasonable to choose larger tunnel cross-sections. Lopez et al. [63] present a system that determines the energy and lighting requirements of road tunnels through the use of photographs at the gates. This can be considered a tool that makes the infrastructure more sustainable by guaranteeing dynamic maintenance over time. Studies [64,65] also provide a new control system for calculation and design—namely, an intelligent control system of road tunnel lighting that can realise the effects of illumination as it moves with a vehicle. When a vehicle is detected, the required luminance of the tunnel's interior is calculated based on changes in the tunnel's external ambient luminance, traffic volume and vehicle speed. The use of LEDs is also discussed [66,67]. The point is to improve the uniformity of the road surface due to daylight increasing the use of light inside the tunnel. As has been illustrated, green energy solutions must also meet an assessment of economic factors. Salata et al. [68] propose a management model that calculates luminous flux through a new predictive control system. Therefore, the economic aspect of sustainability must be addressed by finding solutions for the ventilation [69] and lighting systems of tunnels [70] that also include an economic return on investments made.

In Table 7, a summary of each paragraph is offered. The process flow to achieve results was started from the inclusion criteria in Table 3. Most contributions came from China and Europe, both of which also published highly cited papers. After the bibliometric analysis and graphical categorical comparison of research trends, a detailed summary of each article is presented. Discussion on the contents and limitations are offered in Sections 5 and 6.

Table 7. Summary of subject topic content.

Paragraph	Subject Topic	Summary
4.1	S.1 Sustainable infrastructure	Environmental, economic and social aspects must be evaluated simultaneously to make a tunnel system sustainable. Several studies presented herein summarise the different aspects described above; namely, to be resilient, tunnels must be built with sustainable materials, be equipped with smart systems that monitor their infrastructure, guarantee that safety requirements meet regulations and be designed with an economic evaluation of the road tunnel system's lifetime in mind.
4.2	S.2 Renewable sources	The studies in this section address the issue of renewable resources for tunnels. Most of these studies present solutions that involve the use of PV systems; others propose the use of vegetation to reduce the energy required by portals. Most of the energy required is for the lighting system of the tunnel. Therefore, studies are cited that suggest ways to optimise and improve upon the design of already existing resources.
4.3	S.3 Zero-energy tunnel	The 'zero-energy tunnel' is a hot topic. Major proposals involve technological resources, such as the SCADA system; a point-by-point algorithm; the use of a self-developed software to evaluate the influence of the installation mode and angles of luminaires in the road tunnel; an investigation of reasonable time factors for CO-based emissions; and the use of a sliding plate based on transverse deceleration energy.
4.4	S.4 Tunnel safety lighting	In the context of green solutions, the topic of energy optimisation in lighting systems is most critical. Proposed solutions include exploiting LED lamps for performance uniformity; the use of tension structures through an equation that exploits the structural characteristics of a tunnel to reduce energy consumption; a management model that calculates luminous flux through a predictive control system; and an intelligent control system of road tunnel lighting that realises the effects of illumination as it moves with a vehicle.

5. Discussion

As highlighted in the results section, the topic of energy optimisation is extensively discussed in the literature. Many studies also address issues of clean energy and the functionality of integrated systems required to make tunnels a sustainable infrastructure. In the context of sustainable tunnel design, a sustainability vector [71] is introduced to describe the positive interaction between safety systems and territorial resilience. CIs are a singular point of road networks, and the goal must be to ensure their continuity of service, even in the event of an emergency. In terms of energy, continuity of service requires that renewable sources are integrated with traditional sources and that the energy consumption of safety features is reduced to a bare minimum.

The objective of this review was to examine state-of-the-art green solutions for tunnels, paying special attention to aspects of their sustainability and safety. Below are the outputs of the selected documents (many articles can be considered as a knowledge base for green tunnel developments):

- Most articles presented in the results section are conceptual, and the proposed solutions and methodologies are carried out via simulations or analytical models. Although some experimental research has been presented (see Figure 7), this disparity highlights the need to conduct more real-scale tests to verify the feasibility of sustainability solutions;
- The analysis highlighted the need for an economic return [68,70] on the use of renewable energy while also guaranteeing ordinary and extraordinary maintenance of the tunnel and risk management of the investment;
- Major trends in the last decade have resulted in the energy optimisation of road luminaires with attention to the problem of light reflectance and the energy needed for the portal gates of the tunnel;
- Reviews report key points of sustainability perspectives [17] for presenting state-of-the-art solutions;
- The 46 articles presented herein show the complex relationship between different elements of a tunnel system: tunnel lighting, energy consumption and safety. This demonstrates how engineering can be considered as a whole when different subjects are connected through the principles of sustainability;
- From the results, a clear direction appears. Most studies apply experimental research and theoretical frameworks to the issue of tunnel lighting. This is due to strict regulations that impose mandatory parameters on tunnels. If we consider what the state-of-the-art is now, we can work to change the design priorities. For example, if we can demonstrate a way to secure the same amount of energy through the use of alternative sources, we could then design and enact systems from this starting point and not be obligated to adjust engineering design to accommodate regulations. By doing so, we can achieve a sustainable and resilient tunnel infrastructure.

6. Conclusions and Future Directions

An overview of scientific research on green tunnel solutions from the last decade (2013–2022) has been presented with the aim of decreasing the energy required to operate a tunnel system. A synthesis of the results includes possible solutions for protecting the environment and enhancing the resilience and reliability of this particular infrastructure. The main change that occurred during the decade in question, and especially after the Paris Agreement, was the gradual social, economic and environmental approach to the issue of sustainability of critical infrastructures (CI) that accompanied a growing awareness of renewable resources and how to exploit them.

This literature review presents obvious limitations. Over the last several years, the use of green energy for sustainability goals has been discussed from various points of view. The decision to make selections based solely on a consideration of tunnel infrastructure and to limit this consideration to the engineering and energy fields, despite social and ethical themes involved, was motivated by the need to verify the scientific validity of currently proposed solutions. The results of this study cannot be considered complete because the sustainability of critical infrastructures includes the consideration of other relevant issues. Despite this, the proposed criteria for data analysis and the synthesis of results in this review can be considered a basis for further research on tunnel energy and safety systems, as well as their economic implications [70].

The goal of a zero-energy tunnel that uses renewable energy translates into designing a conceptual tunnel with a newly defined energy supply. Minimising specific energy consumption to ensure both user comfort and operational sustainability is not detached from the minimum specific risks of tunnel systems in accordance with Directive 2004/54/EC and Italian Decree 264/2006 [72]. The challenge lies in collecting all perspectives of CI sustainability, including tunnels [73,74]. This review can serve as a point of reference for achieving a near-zero-energy tunnel. Using European [75,76] and American [77] standards as a starting point, safety requirements and a consideration of new technologies can be incorporated to achieve the best design solution.

As underscored in the discussion section, developing a way to generate and store renewable energy entails analysing the economic return of the installation of a green power system, as well as technological innovations in optimising the projects by improving their cost/benefit ratio. The alternative is to obtain exemptions from prescriptive requirements that are not compatible with the real-world context of the project. The aim is to build reliable plants and systems whose performance is subject to performance analysis. In this context, a life cycle assessment is needed to calculate the life cost of the infrastructure's functionality [78]. Tunnels carry out an important role in supporting the economic and social welfare of the nation and must therefore be protected from extreme events.

Extreme events can cause terrible damage to transportation infrastructure and have long-term socio-economic impacts. Thus, in the event of a fire, protection and mitigation systems must work with continuity for the duration of the event. Theoretical energy production must be compared with the actual energy provided to evaluate and optimise system efficiency. A life cycle assessment (following the ISO 14040/ISO 14044) [79,80] can be conducted for structures such as tunnels to address environmental influences throughout their life cycles, from construction to end-of-life, without omitting the operation phase.

One future direction is to link the cited Directive's requirement [75–77] and the energy module of the tunnel using a design based on the probability of a hazardous event occurring. Solutions must be found for the use of renewable energy that provides safety and comfort to users. This will be realised with technologies such as artificial intelligence, Big Data, the Internet of Things and digital twins that advance computational understandings of human behaviour and emergency planning. The goal is to redefine tunnel design and service provision by reducing cost and increasing efficiency and resilience [81].

Overall, the present systematic literature review has led to some practical suggestions. Several research works were highlighted and discussed on the theme of zero-energy road tunnels. An introduction of renewable sources was provided to reduce energy consumption in tunnels. A future challenge would be to combine photovoltaic systems with wind turbines to generate the amount of energy needed [82]. Moreover, to reach the ideal of zero energy, energy storage must be guaranteed for tunnels to become independent. A future direction could involve an autonomous energy module based on wind and solar energy with a storage system. Energy modules calculate the efficiency of wind ventilation and traffic conditions, potential power generation from installed wind turbines at tunnel entrances and PV panels located at portal gates. After having acknowledged the theoretical energy demand, one can realise how much energy is really needed in order to optimise the system. In the initial phase, PV and wind turbines are not installed, and the optimal system design is given by data analysis. Conversely, the management of tunnel ventilation can be oriented towards energy production and/or air quality through a smart predictive system that manages the activation of the system (lighting or ventilation) to ensure the minimum amount of energy is consumed.

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Appendix A

List of selected documents categorised following the subject topic with its referred code and divided as follows:

S.1 Sustainable infrastructure;
S.2 Renewable sources;
S.3 Zero-energy tunnel;
S.4 Safety tunnel lighting.

No	Author	Year	Subject Topic Code
[58]	Yang, C., Fan, S.J.	2013	S.4
[29]	Sauer, J., Fischer, O.	2013	S.1
[60]	Peña-García, A., Gil-Martín, L.M.	2013	S.4
[51]	Lai, W., Liu, X., Chen, W., Lei, X., Cheng, X.	2014	S.2
[46]	Gil-Martín, L.M., Peña-García, A., Jiménez, A., Hernández-Montes, E.	2014	S.2
[61]	Abdul Salam, A.O., Mezher, K.A.	2014	S.4
[66]	Kimura, M., Hirakawa, S., Uchino, H., Motomura, H., Jinno, M.	2014	S.4
[59]	Tsai, M.-S., Lee, X.-H., Lo, Y.-C., Sun, C.-C.	2014	S.4
[39]	Salata, F., Golasi, I., Bovenzi, S., Vollaro, E.L., Pagliaro, F., Cellucci, L., Coppi, M., Gugliermetti, F., Vollaro, A.L.	2015	S.1
[38]	Parise, G., Martirano, L., Parise, L.	2015	S.1
[50]	Peña-García, A., López, J.C., Grindlay, A.L.	2015	S.2
[37]	Parise, G., Martirano, L., Parise, L., Carrarini, L., Mitolo, M.	2015	S.1
[62]	Schranil S.; Stachetzki J.	2015	S.4
[28]	Tarada F.	2015	S.1
[70]	Salata, F.; Golasi, I.; Bombelli, E.; De Lieto Vollaro, E.; Nardecchia, F.; Pagliaro, F.; Gugliermetti, F.; De Lieto Vollaro, A.L.	2015	S.4
[33]	Moretti, L., Cantisani, G., Di Mascio, P.	2016	S.1
[45]	Peña-García, A., Gil-Martín, L.M., Hernández-Montes, E.	2016	S.2
[70]	Salata, F., Golasi, I., Poliziani, A., Futia, A., Vollaro, E.L., Coppi, M., Vollaro, A.L.	2016	S.4
[31]	Makana L.O.; Jefferson I.; Hunt D.V.L.; Rogers C.D.F.	2016	S.1
[54]	Guo, C., Xu, J., Yang, L., Guo, X., Zhang, Y., Wang, M.	2017	S.3
[49]	Yang, C., Fan, S.	2017	S.2
[43]	Galmarini, G., Dell'Agostino, S., Gobbi, M., Mastinu, G.	2017	S.2
[42]	Peña-García, A.	2017	S.2
[65]	Qin, L., Dong, L., Xu, W., Zhang, L., Yan, Q., Chen, X.	2017	S.4
[47]	García-Trenas, T., López, J.C., Peña-García, A.	2018	S.2
[53]	Yang, C., Li, M., Xiao, Y., Xu, Y.	2018	S.3
[63]	López J.C.; Peña-García A.	2018	S.4
[36]	Bracale, A., Caramia, P., Varilone, P., Verde, P.	2019	S.1
[52]	Doulos, L.T., Sioutis, I., Tsangrassoulis, A., Canale, L., Faidas, K.	2019	S.3
[30]	Farag S.G.	2019	S.1
[67]	Krispel, S., Peyerl, M., Maier, G.	2019	S.4
[56]	Sun, D., Athienitis, A., D'Avignon, K.	2019	S.3
[41]	Petrov, S., Todorov, G., Pachamanov, A.	2019	S.2
[55]	Liu, W., Chen, J., Luo, Y., Shi, Z., Wu, Y., Xu, Z., Dong, F.	2020	S.3
[40]	Peña-García, A., Gómez-Lorente, D.	2020	S.2
[69]	Fang, Y., Shen, J., Chen, J., Wang, J., Li, W.	2020	S.4
[64]	Wang, Y., Cui, Y., Chen, F., Ren, R.	2020	S.4
[17]	Gijzel D.; Bosch-Rekveldt M.; Schraven D.; Hertogh M.	2020	S.1
[34]	Luo Y.; Alaghbandrad A.; Genger T.K.; Hammad A.	2020	S.1
[44]	Zhao, J., Feng, Y., Yang, C.	2021	S.2
[35]	Caldera S.; Mostafa S.; Desha C.; Mohamed S.	2021	S.1
[48]	Peña-García, A.	2022	S.2
[8]	Shen, Y., Deng, Y., Li, T., Zhou, L., Feng, S., Zhu, H.	2022	S.1
[5]	Qi, D., Yang, S., Shu, C., Zhang, X., Wang, L.L., Athienitis, A.	2022	S.3
[57]	Jiang, Z., Jia, C., Zheng, P., Gong, Y., Li, N., Ahmed, A., Zhang, Z., Luo, D.	2022	S.3
[32]	Bergman F.; Anderberg S.; Krook J.; Svensson N.	2022	S.1

References

1. United Nations Take Action for the Sustainable Development Goals. Available online: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed on 20 September 2022).
2. Kranz, J.; Schwichow, M.; Breitenmoser, P.; Niebert, K. The (Un)political Perspective on Climate Change in Education—A Systematic Review. *Sustainability* **2022**, *14*, 4194. [CrossRef]
3. PIARC Technical Committee 3.3 Road Tunnel Operation. *Road Tunnel Operations: First Steps towards a Sustainable Approach*; (Technical Report 2017RO2EN); PIARC Technical Committee 3.3 Road Tunnel Operation: Paris, France, 2017.
4. Adden, H.; Engelhardt, S.; Friebel, W.D.; Lehan, A.; Schwarz, J.; Speier, L.; Thewes, M.; Vogt, P. *Recommendations for the Determination of Lifecycle Costs for Road Tunnels*; German Tunnelling Committee (DAUB): Cologne, Germany, November 2018.
5. Qi, D.; Yang, S.; Shu, C.; Zhang, X.; Wang, L.L.; Athienitis, A. An exploratory study on road tunnel with semi-transparent photovoltaic canopy—From energy saving and fire safety perspectives. *Build. Simul.* **2022**, *15*, 537–548. [CrossRef]
6. Mehri, A.; Hajizadeh, R.; Dehghan, S.F.; Nassiri, P.; Jafari, S.M.; Taheri, F.; Zakerian, S.A. Safety Evaluation of the Lighting at the Entrance of a Very Long Road Tunnel: A Case Study in Ilam. *Saf. Health Work.* **2017**, *8*, 151–155. [CrossRef] [PubMed]
7. Parise, G.; Lombardi, M. Ethics and Eco-Design for Complex Uses of Energy: What We Need for a Sustainable Future. *IEEE Ind. Appl. Mag.* **2022**, *28*, 74–79. [CrossRef]
8. Shen, Y.; Deng, Y.; Li, T.; Zhou, L.; Feng, S.; Zhu, H. Determining multidimensional diffuse reflection effects in city tunnel lighting environment. *Build. Environ.* **2022**, *212*, 108796. [CrossRef]
9. Shen, Y.; Ling, J.; Li, T.; Zhou, L.; Feng, S.; Zhu, H. Diffuse reflection-based lighting calculation model and particle swarm optimization algorithm for road tunnels. *Tunn. Undergr. Space Technol.* **2022**, *124*, 104457. [CrossRef]
10. Huy Majer, M.; Woegerbauer, M.; Winkler, L.; Mazak-Huemer, A.; Biedermann, H. An Interdisciplinary Systematic Review on Sustainability in Tunneling—Bibliometrics, Challenges, and Solutions. *Sustainability* **2022**, *14*, 2275. [CrossRef]
11. PRISMA. Prisma—Transparent Reporting of Systematic Reviews and Meta-Analyses. Available online: http://prisma-statement.org/ (accessed on 20 September 2022).
12. Prisma Flow Diagram. Available online: https://www.prisma-statement.org//PRISMAStatement/FlowDiagram (accessed on 30 September 2022).
13. Elsevier. Scopus—Document Search. Available online: https://www.scopus.com (accessed on 20 September 2022).
14. United Nations. The Sustainable Development Agenda. Available online: https://www.un.org/sustainabledevelopment/development-agenda/ (accessed on 20 September 2022).
15. Baas, J.; Schotten, M.; Plume, A.; Côté, G.; Karimi, R. Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quant. Sci. Stud.* **2020**, *1*, 377–386. [CrossRef]
16. Falagas, M.E.; Pitsouni, E.I.; Malietzis, G.A.; Pappas, G. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *FASEB J.* **2007**, *22*, 338–342. [CrossRef]
17. Gijzel, D.; Bosch-Rekveldt, M.; Schraven, D.; Hertogh, M. Integrating sustainability into major infrastructure projects: Four perspectives on sustainable tunnel development. *Sustainability* **2020**, *12*, 6. [CrossRef]
18. Barry, J.; Proops, J. Seeking sustainability discourses with Q methodology. *Ecol. Econ.* **1999**, *28*, 337–345. [CrossRef]
19. Scimago Compare Journal. Available online: https://www.scimagojr.com/comparejournals.php?ids[]=29593 (accessed on 30 September 2022).
20. Scimago Journal Rank. Available online: https://www.scimagojr.com/journalrank.php?category=2603 (accessed on 30 September 2022).
21. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
22. Broadus, R.N. Toward a definition of "bibliometrics". *Scientometrics* **1987**, *12*, 373–379. [CrossRef]
23. Glänzel, W.; Schubert, A. Analysing Scientific Networks Through Co-Authorship. In *Handbook of Quantitative Science and Technology Research*; Moed, H.F., Glänzel, W., Schmoch, U., Eds.; Springer: Dordrecht, The Netherland, 2004; pp. 257–276. [CrossRef]
24. Zeng, L.; Li, R.Y.M.; Nuttapong, J.; Sun, J.; Mao, Y. Economic Development and Mountain Tourism Research from 2010 to 2020: Bibliometric Analysis and Science Mapping Approach. *Sustainability* **2022**, *14*, 562. [CrossRef]
25. Van Eck, N.J.; Waltman, L. Visualizing bibliometric networks. In *Measuring Scholarly Impact: Methods and Practice*; Ding, Y., Rousseau, R., Wolfram, D., Eds.; Springer: Cham, Switzerland, 2014; pp. 285–320. [CrossRef]
26. Scimago Viztools. Available online: https://www.scimagojr.com/viztools.php (accessed on 30 September 2022).
27. Regufe, M.J.; Pereira, A.; Ferreira, A.F.P.; Ribeiro, A.M.; Rodrigues, A.E. Current Developments of Carbon Capture Storage and/or Utilization–Looking for Net-Zero Emissions Defined in the Paris Agreement. *Energies* **2021**, *14*, 2406. [CrossRef]
28. Tarada, F. Is Tunnel Ventilation Sustainable? Available online: https://mosen.global/wpcontent/uploads/2011/01/Is-Tunnel-Ventilation-Sustainable.pdf (accessed on 20 September 2022).
29. Sauer, J.; Fischer, O. Sustainability considerations for tunnel projects. In *Research and Applications in Structural Engineering, Mechanics and Computation, Proceedings of the 5th International Conference on Structural Engineering, Mechanics and Computation (SEMC 2013), Cape Town, South Africa, 2–4 September 2013*; CRC Press: Boca Raton, FL, USA, 2013; pp. 2463–2466.
30. Farag, S.G. Application of Smart Structural System for Smart Sustainable Cities. In Proceedings of the 2019 4th MEC International Conference on Big Data and Smart City (ICBDSC), Muscat, Oman, 15–16 January 2019. [CrossRef]

31. Makana, L.O.; Jefferson, I.; Hunt, D.V.L.; Rogers, C.D.F. Assessment of the future resilience of sustainable urban sub-surface environments. *Tunn. Undergr. Space Technol.* **2016**, *55*, 21–31. [CrossRef]
32. Bergman, F.; Anderberg, S.; Krook, J.; Svensson, N. A Critical Review of the Sustainability of Multi-Utility Tunnels for Colocation of Subsurface Infrastructure. *Front. Sustain. Cities* **2022**, *4*, 847819. [CrossRef]
33. Moretti, L.; Cantisani, G.; Di Mascio, P. Management of road tunnels: Construction, maintenance and lighting costs. *Tunn. Undergr. Space Technol.* **2016**, *51*, 84–89. [CrossRef]
34. Luo, Y.; Alaghbandrad, A.; Genger, T.K.; Hammad, A. History and recent development of multi-purpose utility tunnels. *Tunn. Undergr. Space Technol.* **2020**, *103*, 103511. [CrossRef]
35. Caldera, S.; Mostafa, S.; Desha, C.; Mohamed, S. Exploring the Role of Digital Infrastructure Asset Management Tools for Resilient Linear Infrastructure Outcomes in Cities and Towns: A Systematic Literature Review. *Sustainability* **2021**, *13*, 11965. [CrossRef]
36. Bracale, A.; Caramia, P.; Varilone, P.; Verde, P. Probabilistic Estimation of the Energy Consumption and Performance of the Lighting Systems of Road Tunnels for Investment Decision Making. *Energies* **2019**, *12*, 1488. [CrossRef]
37. Parise, G.; Martirano, L.; Parise, L.; Carrarini, L.; Mitolo, M. The Electrical Systems of Roadway Tunnels: Safety Design and Ecomanagement. *IEEE Trans. Ind. Appl.* **2014**, *51*, 1920–1927. [CrossRef]
38. Parise, G.; Martirano, L.; Parise, L. The energetic impact of the lighting system in the road tunnels. In Proceedings of the 2015 IEEE/IAS 51st Industrial & Commercial Power Systems Technical Conference (I&CPS), Calgary, AB, Canada, 5–8 May 2015; pp. 1–7. [CrossRef]
39. Salata, F.; Golasi, I.; Bovenzi, S.; Vollaro, E.; Pagliaro, F.; Cellucci, L.; Coppi, M.; Gugliermetti, F.; Vollaro, A. Energy Optimization of Road Tunnel Lighting Systems. *Sustainability* **2015**, *7*, 9664–9680. [CrossRef]
40. Peña-García, A.; Gómez-Lorente, D. Installation of solar panels in the surroundings of tunnel portals: A double-targeted strategy to decrease lighting requirements and consumption. *Tunn. Undergr. Space Technol.* **2020**, *97*, 103251. [CrossRef]
41. Petrov, S.; Todorov, G.; Pachamanov, A. Island photovoltaic tunnel lighting systems. In Proceedings of the 2019 Second Balkan Junior Conference on Lighting (Balkan Light Junior), Plovdiv, Bulgaria, 19–21 September 2019; pp. 1–4. [CrossRef]
42. Peña-García, A. The SLT equation: A tool to predict and evaluate energy savings in road tunnels with sunlight systems. *Tunn. Undergr. Space Technol.* **2017**, *64*, 43–50. [CrossRef]
43. Galmarini, G.; Dell'Agostino, S.; Gobbi, M.; Mastinu, G. *Solar Prototype for Shell-Eco Marathon Racep*; SAE Technical Paper: Detroit, MI, USA, 2017; Volume 1, p. 1260. [CrossRef]
44. Zhao, J.; Feng, Y.; Yang, C. Intelligent control and energy saving evaluation of highway tunnel lighting: Based on three-dimensional simulation and long short-term memory optimization algorithm. *Tunn. Undergr. Space Technol.* **2020**, *109*, 103768. [CrossRef]
45. Peña-García, A.; Gil-Martín, L.M.; Hernández-Montes, E. Use of sunlight in road tunnels: An approach to the improvement of light-pipes' efficacy through heliostats. *Tunn. Undergr. Space Technol.* **2016**, *60*, 135–140. [CrossRef]
46. Gil-Martín, L.M.; Peña-García, A.; Jiménez, A.; Hernández-Montes, E. Study of light-pipes for the use of sunlight in road tunnels: From a scale model to real tunnels. *Tunn. Undergr. Space Technol.* **2014**, *41*, 82–87. [CrossRef]
47. García-Trenas, T.; López, J.C.; Peña-García, A. Proposal to forest Alpine tunnels surroundings to enhance energy savings from the lighting installations. Towards a standard procedure. *Tunn. Undergr. Space Technol.* **2018**, *78*, 1–7. [CrossRef]
48. Peña-García, A. Sustainable tunnel lighting: One decade of proposals, advances and open points. *Tunn. Undergr. Space Technol.* **2021**, *119*, 104227. [CrossRef]
49. Yang, C.; Fan, S. Parameters Optimization and Energy-Saving of Highway Tunnel Backlighting with LED. *J. Donghua Univ.* **2017**, *34*, 9–13.
50. Peña-García, A.; López, J.C.; Grindlay, A.L. Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants. *Tunn. Undergr. Space Technol.* **2015**, *46*, 111–115. [CrossRef]
51. Lai, W.; Liu, X.; Chen, W.; Lei, X.; Cheng, X. Optimization optical design for tunnel lamps with LED source. In Proceedings of the 2014 11th China International Forum on Solid State Lighting (SSLCHINA), Guangzhou, China, 6–8 November 2014; pp. 154–157. [CrossRef]
52. Doulos, L.T.; Sioutis, I.; Tsangrassoulis, A.; Canale, L.; Faidas, K. Minimizing lighting consumption in existing tunnels using a no-cost fine-tuning method for switching lighting stages according revised luminance levels. In Proceedings of the 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Genova, Italy, 11–14 June 2019; pp. 1–6. [CrossRef]
53. Yang, C.; Li, M.; Xiao, Y.; Xu, Y. Influence of Light Distribution and Installation Style of Luminaires on Power Consumption and Lighting Effect of Tunnel Lighting. *Mod. Tunn. Technol.* **2018**, *55*, 131–138. [CrossRef]
54. Guo, C.; Xu, J.; Yang, L.; Guo, X.; Zhang, Y.; Wang, M. Energy-Saving Network Ventilation Technology of Extra-Long Tunnel in Climate Separation Zone. *Appl. Sci.* **2017**, *7*, 454. [CrossRef]
55. Liu, W.; Chen, J.; Luo, Y.; Shi, Z.; Wu, Y.; Xu, Z.; Dong, F. Investigation on the Time Factor of CO-Based Emission Factors for Sustainable Development of Urban Tunnels in China. *Adv. Civ. Eng.* **2020**, *2020*, 8843943. [CrossRef]
56. Sun, D.; Athienitis, A.; D'Avignon, K. Application of semitransparent photovoltaics in transportation infrastructure for energy savings and solar electricity production: Toward novel net-zero energy tunnel design. *Prog. Photovolt. Res. Appl.* **2018**, *27*, 1034–1044. [CrossRef]

57. Jiang, Z.; Jia, C.; Zheng, P.; Gong, Y.; Li, N.; Ahmed, A.; Zhang, Z.; Luo, D. A transverse deceleration energy harvester based on a sliding plate for self-powered applications in near-zero energy road tunnels. *Sustain. Cities Soc.* **2022**, *84*, 104014. [CrossRef]
58. Yang, C.; Fan, S. Energy-Saving Performance Studies of Road Tunnel Luminaries. *Appl. Mech. Mater.* **2013**, *291–294*, 654–660. [CrossRef]
59. Tsai, M.S.; Lee, X.H.; Lo, Y.C.; Sun, C.C. Optical design of tunnel lighting with white light-emitting diodes. *Appl. Opt.* **2014**, *53*, H114–H120. [CrossRef]
60. Peña-García, A.; Gil-Martín, L.M. Study of pergolas for energy savings in road tunnels. Comparison with tension structures. *Tunn. Undergr. Space Technol.* **2013**, *35*, 172–177. [CrossRef]
61. Salam, A.A.; Mezher, K. Energy Saving in Tunnels Lighting using Shading Structures. In Proceedings of the International Renewable and Sustainable Energy Conference (IRSEC), Ouarzazate, Marocco, 17–19 October 2014; pp. 519–524. [CrossRef]
62. Schrani, S.; Stachetzki, J. Energetic optimization of cross-sections of tunnels. *Elektr. Bahnen* **2015**, *113*, 488–497.
63. López, J.C.; Peña-García, A. Determination of lighting and energy demands of road tunnels using vehicle based photographs of the portal gates: An accessible and safe tool for tunnel renewal and maintenance. *Tunn. Undergr. Space Technol.* **2018**, *78*, 8–15. [CrossRef]
64. Wang, Y.; Cui, Y.; Chen, F.; Ren, R. An Illumination Moving with the Vehicle Intelligent Control System of Road Tunnel Lighting. *Sustainability* **2020**, *12*, 7314. [CrossRef]
65. Qin, L.; Dong, L.; Xu, W.; Zhang, L.; Yan, Q.; Chen, X. A Vehicle in, light brightens; vehicle out, light darkens energy-saving control system of highway tunnel lighting. *Tunn. Undergr. Space Technol.* **2017**, *66*, 147–156. [CrossRef]
66. Kimura, M.; Hirakawa, S.; Uchino, H.; Motomura, H.; Jinno, M. Energy Savings in Tunnel Lighting by Improving the Road Surface Luminance Uniformity—A New Approach to Tunnel Lighting. *J. Light Vis. Environ.* **2014**, *38*, 66–78. [CrossRef]
67. Krispel, S.; Peyerl, M.; Maier, G. Enhancing safety whilst saving energy in tunnels due to an optimised choice of road surface materials. *Bautechnik* **2019**, *96*, 499–508. [CrossRef]
68. Salata, F.; Golasi, I.; Poliziani, A.; Futia, A.; De Lieto Vollaro, E.; Coppi, M.; De Lieto Vollaro, A. Management Optimization of the Luminous Flux Regulation of a Lighting System in Road Tunnels. A First Approach to the Exertion of Predictive Control Systems. *Sustainability* **2016**, *8*, 1092. [CrossRef]
69. Fang, Y.; Shen, J.; Chen, J.; Wang, J.; Li, W. Study on Fire Smoke Characteristic in Double-tube Road Tunnel with Complementary Ventilation System. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *741*, 012108. [CrossRef]
70. Salata, F.; Golasi, I.; Bombelli, E.; De Lieto Vollaro, E.; Nardecchia, F.; Pagliaro, F.; Gugliermetti, F.; De Lieto Vollaro, A. Case Study on Economic Return on Investments for Safety and Emergency Lighting in Road Tunnels. *Sustainability* **2015**, *7*, 9809–9822. [CrossRef]
71. López, J.C.; Grindlay, A.L.; Peña-García, A. A proposal for evaluation of energy consumption and sustainability of road tunnels: The sustainability vector. *Tunn. Undergr. Space Technol.* **2017**, *65*, 53–61. [CrossRef]
72. European Parliament and Council. Directive 2004/54/EC. Official Journal of the European Union. L.167, Bruxelles. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32004L0054 (accessed on 30 September 2022).
73. Amin, M. Challenges in reliability, security, efficiency, and resilience of energy infrastructure: Toward smart self-healing electric power grid. In Proceedings of the Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008; pp. 1–5. [CrossRef]
74. IEEE Smart Cities. About Smart Cities. Available online: https://www.ieee-pes.org/pes-communities/ieee-smart-cities (accessed on 20 September 2022).
75. *CIE 88-2004*; Guide for the Lighting of Tunnels and Underpasses. International Commission on Illumination: Vienna, Austria, 2004.
76. *CIE 140-2000*; Road Lighting Calculations. International Commission on Illumination: Vienna, Austria, 2000.
77. *ANSI/IESNA RP-22-96*; American National Standard Practice for Tunnel Lighting. Illuminating Engineering Society of North America: New York, NY, USA, 1996.
78. Sun, W.; Bocchini, P.; Davison, B.D. Resilience metrics and measurement methods for transportation infrastructure: The state of the art. *Sustain. Resilient Infrastruct.* **2018**, *5*, 168–199. [CrossRef]
79. *ISO 14040*; Environmental Management–Life Cycle Assessment–Principles and Framework. International Standard Organization: Geneva, Switzerland, October 2006; 20p.
80. *ISO 14044*; Environmental Management–Life Cycle Assessment–Requirements and Guidelines. International Standard Organization: Geneva, Switzerland, October 2006; 46p.
81. Allam, Z.; Bibri, S.E.; Chabaud, D.; Moreno, C. The Theoretical, Practical, and Technological Foundations of the 15-Minute City Model: Proximity and Its Environmental, Social and Economic Benefits for Sustainability. *Energies* **2022**, *15*, 6042. [CrossRef]
82. Dzhusupova, R.; Cobben, J.F.G.; Kling, W.L. Zero energy tunnel: Renewable energy generation and reduction of energy consumption. In Proceedings of the 47th International Universities Power Engineering Conference (UPEC), Uxbridge, UK, 4–7 September 2012; pp. 1–6. [CrossRef]