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Towards sustainable nocturnal environment management: a social-ecological-technical system analysis in Wallonia (Belgium)

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Abstract
This study examines the management of the nocturnal environment in Belgium's Walloon region from a social-ecological-technical system perspective, aiming to enhance sustainability in nightscapes. To identify critical challenges and action priorities, we employ Political, Economic, Social, Technological, Environmental, and Legal analysis. Our research offers insights into the macro-environmental factors that organisations should prioritise when envisioning sustainable lighting and dark sky protection. Based on the outcomes of the Walloon case study and the recent literature, we determine the priorities that lead to shaping action plans and the research challenges to ensure a smooth transition towards more sustainable nightscapes. Key challenges emerge: a lack of awareness of light pollution, both for the authorities and citizens; a longstanding relationship between safety and lighting, with fears echoed in political discourse; and the lack of consideration of light pollution in legal, political and environmental agendas. To address these challenges, enhanced policies could be tailored to local contexts and improved to mitigate light pollution. Findings support a multidimensional strategy integrating public action with awareness campaigns, encouraging sustainable practices in management of nocturnal environments.

Keywords Social-ecological-technical systems · Nocturnal environment management · Sustainable public lighting · PESTEL analysis · Light pollution

1 Introduction

The recent years have witnessed a rapid increase in the intensity and amount of light emitted into the nocturnal environment [51, 56, 83], a considerable part of which stems from public lighting [19].

The implications of artificial light at night (ALAN) extend beyond mere environmental concerns, affecting human health, wildlife, and the visibility of stars [22, 51, 81, 83, 122, 123, 129, 143, 163]. Despite the growing recognition of these issues [23, 35, 150], policy responses often remain narrowly focused on energy efficiency or technical aspects rather than a holistic view of nocturnal ecology [21, 64, 127]. The environmental requalification of public lighting prompts the consideration of the nocturnal environment as a Social-Ecological System (SES) undergoing technological, ecological, and territorial mutations [21].

A SES is defined as "an ecological system intricately linked with and affected by one or more social systems" [6]. As discussed by McGinnis and Ostrom [91], the SES framework provides a valuable theoretical tool for analysing the complex interactions

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between social and ecological systems. This framework helps to understand how governance systems can be structured to sustain ecological resources. Additionally, the extension to Social-Ecological-Technical Systems (SETS) acknowledges the critical role of technological systems within these interactions, highlighting the importance of considering technological infrastructure and its impacts on both ecological and social dynamics [91].

The shift of public lighting towards new technologies, such as light-emitting diodes (LEDs), presents both challenges and opportunities. While LEDs are known for their energy efficiency and longevity, their introduction could inadvertently contribute to increased light pollution if not managed carefully [57, 136].

In Belgium, by extension in the Walloon region (French- and German-speaking part of Belgium), the intensity of nocturnal lighting is evident from satellite imagery [50, 52]. The Ministry of the Environment of the Czech Republic [95] describes the country as one of the most illuminated and relates most of this excess to public and road lighting. Ongoing projects aim to renew the public lighting infrastructure, with investments set to finish by the decade's end [85, 109]. The transition in Wallonia is less advanced than in Belgium's Flanders region (Dutch-speaking part of Belgium) [54, 110]. Concerns arise because the period from 2014 to 2020 globally witnessed a significant shift in the spectral composition of lighting, transitioning from the glow of high-pressure sodium lamps to broader-spectrum white LEDs, which emit more blue light and potentially increase ecological disturbances [65, 128]. Finally, discussions revolve around potential municipal streetlight reduction due to the energy crisis [14], and the upholding of these decisions.

While it is often claimed that public lighting is the main source of light pollution, studies in locations such as Tucson, USA, suggest that private outdoor lighting significantly contributes to the problem, particularly following the switch to LED technology [10, 79]. In the Walloon region, however, private lighting is estimated to account for a quarter of the nighttime pollution [74]. Nonetheless, the most effective awareness campaign for sustainable practices is public action that leads by example. Sustainable management of the nocturnal environment can significantly influence private behaviour and encourage wider adoption beyond its direct environmental benefits [74].

Given the complexity of the nocturnal environment as SES, there is a pressing need to integrate diverse research perspectives to develop nature-based management and sustainable lighting solutions [21, 22, 154]. This study aims to explore sustainable management practices for the Walloon nocturnal environment within the SETS framework, highlighting their role in achieving the Sustainable Development Goals (SDGs) developed by the United Nations [29, 112, 152].

To address the practical and theoretical gaps in current research, this paper employs a Political, Economic, Social, Technological, Environmental, and Legal (PESTEL) analysis. This tool is selected for its ability to comprehensively assess the macro-environmental factors influencing the management of the nocturnal environment. The method has already been applied to other industries, for instance, tourism [60] and waste-to-energy incineration industries [142]. The preference for PESTEL over other tools, such as the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis [63] or Porter's Five Forces [121] is informed by the needs of this study. Specifically, PESTEL's comprehensive scope is crucial for addressing the extensive macro-environment of the actors of the nocturnal environment in Wallonia, while SWOT and Porter's Five Forces are more adapted to internal and competitive business factors.

By fusing the insights from this analysis and from the recent literature, we spotlight critical contextual factors, pave the way for actionable recommendations for practitioners and scholars, updating the agenda of Hölker et al. [64], to steer a successful transition towards more sustainable public lighting management.

Therefore, this research addresses the following question: what are the key challenges for transitioning towards sustainable management of the Walloon nocturnal environment?

The remainder of the paper is structured as follows. In Sect. 2, we determine the theoretical background of this research. Then, the methodology is presented in Sect. 3. The outcomes of the PESTEL analysis are developed in Sect. 4. Furthermore, we envision lines of actions in Wallonia and potential leads for future research to promote sustainable nocturnal environments globally, as discussed in Sect. 5. We present our conclusions in Sect. 6. Throughout the developments in this paper, *municipalities* (and its derivations) and *local authorities* are used as synonyms.

2 Research background

This study builds on the proposal by Challéat [21] to study the nocturnal environment as a SES. It extends this concept to that of SETS. Methodologically, it is placed in the regional dimension, and makes use of the methodological pluralism of the field by inviting a widely used tool from the management realm. Practically, our research at the intersection of sustainable management and public lighting addresses the urgent requirement for a thorough analysis of macro-environmental factors. In this section, we summarise the theoretical background.

2.1 SES research: a framework for integrating evidence into policy processes

SES are presented as "cohesive, integrated systems characterised by strong connections and feedbacks within and between social and ecological components that determine their overall dynamics" [16 p. 5]. Amin et al. [5] highlighted that the SES framework has been employed to comprehend the intricacies of regional sustainability, including its effects on ecosystem services, transformation systems, product accommodation, fisheries, and water management. SETS extend the scope of SES in that they include technical systems. McGinnis and Ostrom [91] differentiated the frameworks by contrasting the natural ecological dynamics of SES with the complex, constructed technical dynamics of SETS. A second significant difference between both frameworks is the interaction between the SETS and the primary users, who expect continuous service provision, as opposed to discrete units in SES [2, 91].

The interdisciplinary approach is essential for studying the nocturnal environment within the SETS framework, as emphasised by Challéat [21]. SETS are composed of resource units and systems, actors, governance systems, and the related ecosystems and social, economic, and political settings [91, 112]. In the case of the nocturnal environment, the resources comprise the darkness, starry sky, access to the nocturnal environment, and ecosystem services rendered by the biodiversity, as well as the natural resources depleted during the life cycle of the lighting infrastructure. The users are the population at large, in diverse activities with antagonistic positions towards ALAN (star gazers, endangered species, night dwellers, night workers, experts, etc.). The related physical public infrastructure is provided by the local authorities and distribution system operators (DSOs).

Research on SES aims to stimulate the integration of evidence and scientific knowledge into policy processes. The field is problem-driven and action-oriented, focusing on informing sustainable practices [16, 33, 131]. The framework is valuable in examining how users can organise to manage the resources sustainably [16].

Methodological pluralism characterises SES research, reflecting a broad range of methods, tools, and approaches applicable to various studies [16, 17, 33]. Such diversity in methodologies supports the adaptation of specific approaches [131] like PESTEL analysis, which has been effectively used in environmental management to establish strategic objectives [162]. In light of this, our study employs the PESTEL framework to analyse the macro-environmental dimensions of the nocturnal environment in Wallonia, which to our knowledge, has not been investigated. This study represents an example endeavour that could, in turn, be appropriated by local authorities to implement actionable insights into sustainable management practices.

2.2 Sustainable management of the nocturnal environment

Salvia et al. [127] and da Silva et al. [29] identify scarce literature on sustainable public lighting management and concurrently notice an unexplored area between sustainable management and public lighting. Moreover, Rodrigo-Comino et al. [123] reveal the isolation of critical stakeholders from the scientific community as far as decisions on light pollution mitigation are concerned and detect a need for more sustainable management plans. The authors refer to Hölker et al. [64], who insist on the imperative of managing darkness and developing sustainable (socially, ecologically, and economically) lighting technologies and concepts. In turn, da Silva et al. [29] argue that sustainable public lighting management exceeds these three pillars of sustainability. We suggest completing their consideration to reach the PESTEL framework.

Recent analyses of the macro-environmental context of public lighting management [1, 29, 72, 108, 152] and of dark sky protection [12, 86, 87, 139] have highlighted a common limitation: they do not fully integrate all dimensions of the PESTEL framework. Abdullahi et al. [1] provide a decision-support tool to design lighting scenarios that focuses on economic, social (limited to required light level), and environmental (limited to carbon emissions) criteria. Barriers to effective and sustainable public lighting management, as identified by Kasseh et al. [72], include economic, technological, and legal elements. The Energy Action Plan proposed by Neves et al. [108], which ranks public lighting actions as a priority, relies on identifying the economic, social, technological, and environmental contextual elements. Finally, the solutions highlighted by da Silva et al. [29] are based on economic, social, and environmental context elements. From Table 1, we observe that the macro-environmental analyses consistently lack to consider the political element of the PESTEL framework, except Silver and Hickey [139], and that they omit either the social [72], technological [1, 29, 86], environmental [72], or legal [1, 12, 29, 86, 87, 108] elements, while the economic element is not considered by Beeco et al. [12] and Lyytimäki [86]. Most strategies proposed in these studies focus predominantly on improved regulatory framework [152] and awareness-raising activities [12, 29, 152] or consist in practical lighting scenarios [1, 108]. Bottom-up influence on authorities by individuals or activists is suggested by Lyytimäki [87] and Silver and Hickey [139] for light pollution management. Dark sky tourism is a strategy that could yield economic, social, and ecological benefits [12, 139].

Table 1 Macro-environmental Context of the Management of the Nocturnal Environment

Study	Methodology	P	E	S	T	E	L	Findings
Lyytimäki [86]	Literature review of research on light pollution and ecosystem services			✓		✓		The shifting baseline syndrome induces low appreciation of nocturnal nature, as most people are used to ALAN. Increased attention is needed to clarify the best night sky preservation actions
Lyytimäki [87]	Online survey on public opinion on light pollution		✓	✓	✓	✓		The Finnish population considered road lights as the main source of light pollution. Individuals indirectly influence lighting systems through the authorities. Systems intelligence underlines the bottom-up influence of private individuals on light pollution management
Neves et al. [108]	Multi-criteria decision analysis		✓	✓	✓	✓		Implementing the Energy Action Plan could reduce carbon dioxide emissions by up to 3,000 tons annually, focusing on enhancing public lighting, transitioning to biomass pool heaters, and installing solar panels, based on economic viability and stakeholder preferences
Abdullahi et al. [1]	Multicriteria decision-making optimisation model		✓	✓		✓		Implementing energy-efficient lighting technologies through a Decision Support Tool significantly reduces street lighting costs while enhancing economic, environmental, and social impacts in smart cities
Silver and Hickey [139]	Case study (key informant interviews and survey)	✓	✓	✓		✓	✓	Dark sky area (DSA) eased light pollution reductions. Some socio-political barriers could be overcome through activism. DSA tourism potential has economic and environmental appeal
Tavares et al. [152]	Literature review		✓	✓		✓		Outdoor lighting positively influences SDGs 3, 11, 14, 15, 7, and 13 by improving urban safety, energy efficiency and reducing environmental impact
da Silva et al. [29]	Systematic literature survey		✓	✓		✓		Identify gaps: a scarcity of scientific literature on the nexus between sustainable management and public lighting, with the primary practices in this field predominantly occurring in European cities
Beeco et al. [12]	On-site intercept survey (visitors of nine parks in Utah) of support of management actions for night sky protection			✓		✓		Strong support for management actions for night sky quality, and interest in learning activities
Kasseh et al. [72]	Diagnostic incorporating comparisons with international best practices		✓		✓		✓	Identify economic, technological, legal, and human resource barriers, and emphasising the need for adopting public-private partnerships to enhance the governance of public lighting in Morocco

3 Materials and methods

We introduce the study area and the methodology.

3.1 Study area

Wallonia is one of the three regions of Belgium, which ranks sixth country globally in light pollution hindering access to the Milky Way. The totality of the Belgian population and territory is under a polluted sky, i.e. with an artificial sky brightness exceeding 87 $\mu cd/m^2$ corresponding to 50% above natural nighttime brightness [50].

Figure 1 is the nighttime satellite view of the region on 8 March 2024 (overpassing time: 01:32), generated with NASA's Black Marble Suomi National Polar-orbiting Partnership (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS) VNP46A1 [124]. It attests to the coincidence of nighttime radiance with the road network, in accordance with the image of NASA [106].

3.2 Methodology

The methodology includes a data search and the subsequent PESTEL analysis.

Data search The literature search collected data from the Scopus database. To determine the eligibility of the articles, we established the following criteria: full-text accessibility, publication date between 2000 and 2024, and relevance to the subject matter. The first query consisted of the following keywords ("social-ecological-system" OR "SES" OR "STES" OR "social-ecological-technical system" OR "social-technical-ecological system") AND ("public lighting" OR "streetlight*" OR "nocturnal environment"), searched in article title, abstract and keywords. The query generated two results, one of which was out of scope (wind energy). The article by Challéat [21] was the one retained. The second query consisted of the keywords ("management" OR "strategy") AND ("public lighting" OR "streetlight*") AND "sustainable", in article title, abstract and keywords. The search yielded twenty articles. Filtering by consulting the title and abstract to only retain articles on the sustainable management of public lighting allowed to retain four articles [29, 71, 108, 127]. The retained articles were consulted, and one of their references was added to the selection [1]. The third query consisted in the keywords ("nocturnal environment" OR "night environment" OR "dark sky") AND "management", in article title, abstract and keywords. It yielded 23 articles, from which four were retained based on the same filtering criteria [12, 86, 87, 139].

In addition to the literature review, we considered official information on the Walloon region's organisation, political functioning, demographics, and economics, to support the PESTEL analysis as per Johnson et al. [69] and The European Commission [153]. The sources are official statistical agencies in Wallonia and Belgium, the Federal and Regional Public Services, the Walloon Parliament, the regulator (CWaPE, CREG), the representative association of Walloon municipalities (UVCW), Walloon organisations (e.g. LuWa), and foreign institutions.

The programmes of the six political parties represented in Parliament [138] for the 2018 local, and 2019 and 2024 regional elections, Centre démocrate Humain [20], DéFI [38–40], Les Engagés [80], Ecolo [44, 45], Mouvement Réformateur [103–105], Osons Spa [111], Parti du Travail de Belgique [114, 115], Parti Socialiste [116–118] were considered. Some parties did not issue a general programme for the local elections. Hence, we considered the programmes of some local authorities, for DéFI, Les Engagés, and PTB, as examples.

The data on media coverage was collected from the Europresse database [49]. The search period was from 1 January 2014 to 24 May 2024. The keyword searched in all text was "public lighting" (respectively "éclairage public" in French; "öffentliche Beleuchtung", "Straßenbeleuchtung", "Stadtbeleuchtung" in German). The search included all press sources from Belgium (88 sources). The keywords in the two official languages of Wallonia ensured that only French- and German-speaking Belgian press were considered. A total of 4 776 articles were found, of which we retained 1 865 for analysis. Appendix A.1 provides a detailed account of the thematic sorting and subsequent filtering.

Technical information released by the light vendors, DSOs, and lighting institutes are consulted. Legal documents and standards complete the documentary search.

PESTEL analysis To focus on the macro-environment of the nocturnal environment in Wallonia, we employ a PESTEL analysis to examine the perspective of organisations interested in transitioning towards more sustainable practices. The factors are gathered for all six study dimensions, following Johnson et al. [69] and The European Commission [153], and accurate for the object of study. Respectively for each dimension, key drivers for change are: type, organisation, power and role of the state, electoral processes and government change, influence of civil society organisations including the

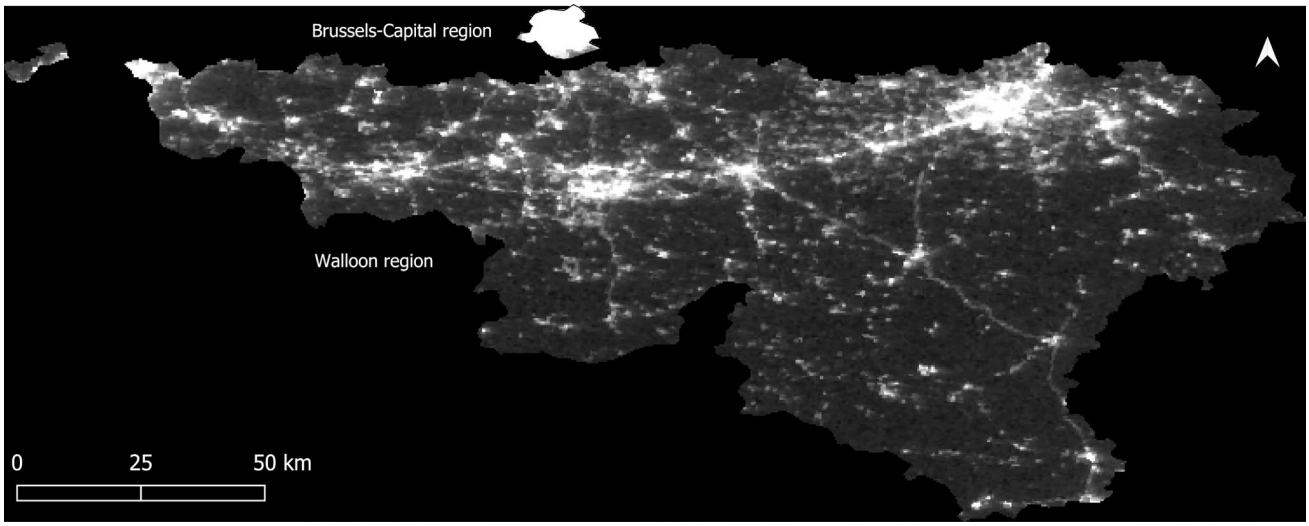

Fig. 1 Nighttime satellite view of Wallonia to the regional border, on 8 March 2024. Own composition based on image courtesy of Román et al. [124], and the NASA Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC), Goddard Space Flight Center, Greenbelt, MD

media and campaign groups, coherence with international commitments (Political), economic growth rate, economic cycle, market typology, pricing (Economic), demographics, social structure, organisational field, culture, social institutions (Social), available technology and dissemination, conformity, engagement in development and research (Technological), pollution, sustainable development, scientific knowledge (Environmental), national and regional legislation, alternative legislation and norms, coherence with international commitments (Legal).

To inform these dimensions, the sources are analysed in different manners. A keyword search of the political parties' programmes examines the coverage and treatment of the subject by quantifying the number of references to public lighting (queries translated from French: "lighting" or "to light") and to preservation initiatives ("night", "starry sky", "nocturnal", "light pollution", "dark corridor", "dark network"), and by considering the context in which the references are stated. The media coverage was analysed based on the thematic sorting developed in Appendix A.1, and each dimension's temporal evolution and relative importance are considered. The institutional, legal, and technical data were directly searched for the other drivers of change.

4 Results: macro-environment of the nocturnal environment in Wallonia (PESTEL analysis)

In this section, we delve into Wallonia's nocturnal environment, and gather the findings of the PESTEL analysis, to identify strategic opportunities and potential threats for sustainable management. Our findings are synthesised in Fig. 3.

4.1 Political dimension

Belgium is a federal state, with power divided into six levels [15]. The regional competencies relate to territorial matters [137]. Regarding infrastructure, the regional authorities are responsible for the streetlights on the main arteries of the network (regional roads and highways), while the 262 municipalities are responsible for the lights present on their territory (municipal light points, whether on-street or not). The region has approximately 750 000 points of public streetlighting, with more than 80% belonging to the municipalities [130]. The municipal authorities own the latter public lighting infrastructure. They are responsible for law enforcement and maintenance of public order [156, 157]. They are empowered by successive Light Plans [125], albeit implemented with varying internal resources.

The Regional Policy Declaration for 2019–2024 [126] does not address light pollution or public lighting. However, this focus may shift with imminent changes in local and territorial governments and their respective policy directions. Indeed, this research was conducted prior to the 2024 regional elections in June and local elections in October (at which point no programme was available). The respective programmes of the political parties set out their stance on the governance of the nocturnal environment. Table 2 provides an overview of the evolution of their consideration

of the nocturnal environment across the 2018, 2019 and 2024 periods. It records the number of instances in which public lighting was mentioned in the programmes. The number of mentions of strategies for dark sky preservation is added in bold.

Overall, the public lighting infrastructure is increasingly considered in political communication at the regional level. For the 2024 elections, "public lighting" was mentioned in the context of safety issues by DéFI [40], Les Engagés [80], Mouvement Réformateur [105], Parti Socialiste [118], respectively two, seven, one, and three times. The four parties explicitly mentioned the safety of women. Hence, the concept of safety has been referenced on 13 occasions out of the 27 instances in which the topic of public lighting has been discussed. Mobility and sustainability are the two other issues considered in the programmes. The Parti Socialiste [118] mentioned the revitalisation of the public space and walkability. Ecolo [45] used "public lighting" in link with biodiversity preservation and mentioned the dark networks twice. Les Engagés [80] used the phrase "public lighting" six times in link with biodiversity, in two sections on light pollution and the erosion of biodiversity. DéFI [40] also mentions dark networks twice. The *maillage noir* in French appears to be the preferred term used by the parties mentioning preservation strategies.

However, light pollution and its intricacies occasionally came with substantial shortcomings in their understanding. For instance, the Socialist party proposed twice to "generalise a smart public lighting system that combines territory security, reasonable energy consumption, and respect for the environment" among which "LED lighting to not harm wildlife" [116 p.74] and [117 p.471], our translation. DéFI [41 p.22] commit to "[generalising] the use of LED bulbs in public lighting", although the Walloon Government issued a Decree organising the replacement of the lighting infrastructure in 2017 [58].

The analysis of media coverage shows that the increased interest in public lighting reduction occurred during the 2022 energy crisis (Appendix A.2). The analysis shows that local governance receives the most media attention, suggesting its prominence in public discussions (Figs. 4 and 5).

Figure 2 summarises the media coverage for 2022–2024, highlighting the media's influence on political decisions concerning the nocturnal environment. The figure represents the importance and evolution of the media concern on the other macro-environmental dimensions. The economic dimension appears to be the most mentioned, in particular in the third and fourth quarters of 2022. This corresponds to the choice given to the authorities to switch off the streetlights. An increase in media coverage of safety and mobility issues can be observed in the aftermath. The legal dimension was mentioned twelve times throughout the 2014–2024 period, with 75% of references to a charter elaborated in one Province in 2019. It is therefore not considered in Fig. 2.

The significant impact of civil society organisations on political decisions, as demonstrated by the activities of campaign groups like ASCEN [9] and Natagora [107], highlights the importance of integrating local environmental and astronomical interests into policy-making. These organisations, composed of astronomers and environmentalists, push for attentiveness to regional specifics and citizen concerns. This situation calls for a tailored approach to policy development, as each region faces unique environmental challenges and regulatory landscapes. Implementing such a tailored policy framework can better accommodate these local specifics, thereby enhancing the solutions' efficacy and ensuring they are suitable for mitigating issues.

4.2 Economic dimension

In 2022, Wallonia's Gross Domestic Product (GDP) amounted to €127 billion, i.e. 23% of the country's GDP [68]. In 2022, the GDP per inhabitant was 87% of the European average. The average annual growth rate of the Walloon GDP

Table 2 Reference to public lighting and strategies for dark sky, in political parties programmes for the 2018, 2019, and 2024 elections (NA: programme not available

	Number of mentions of public lighting (of dark sky)		
Party	2018 (local)	2019 (regional)	2024 (regional)
DéFI	0	NA	7 **(2)**
Ecolo	8 **(1)**	0	1 **(2)**
Les Engagés	0	NA	13 **(2)**
MR	7	3	1
PS	4	4	5
PTB	1	0	0

(Bold numbers): mentions of strategies for dark sky, otherwise not mentioned

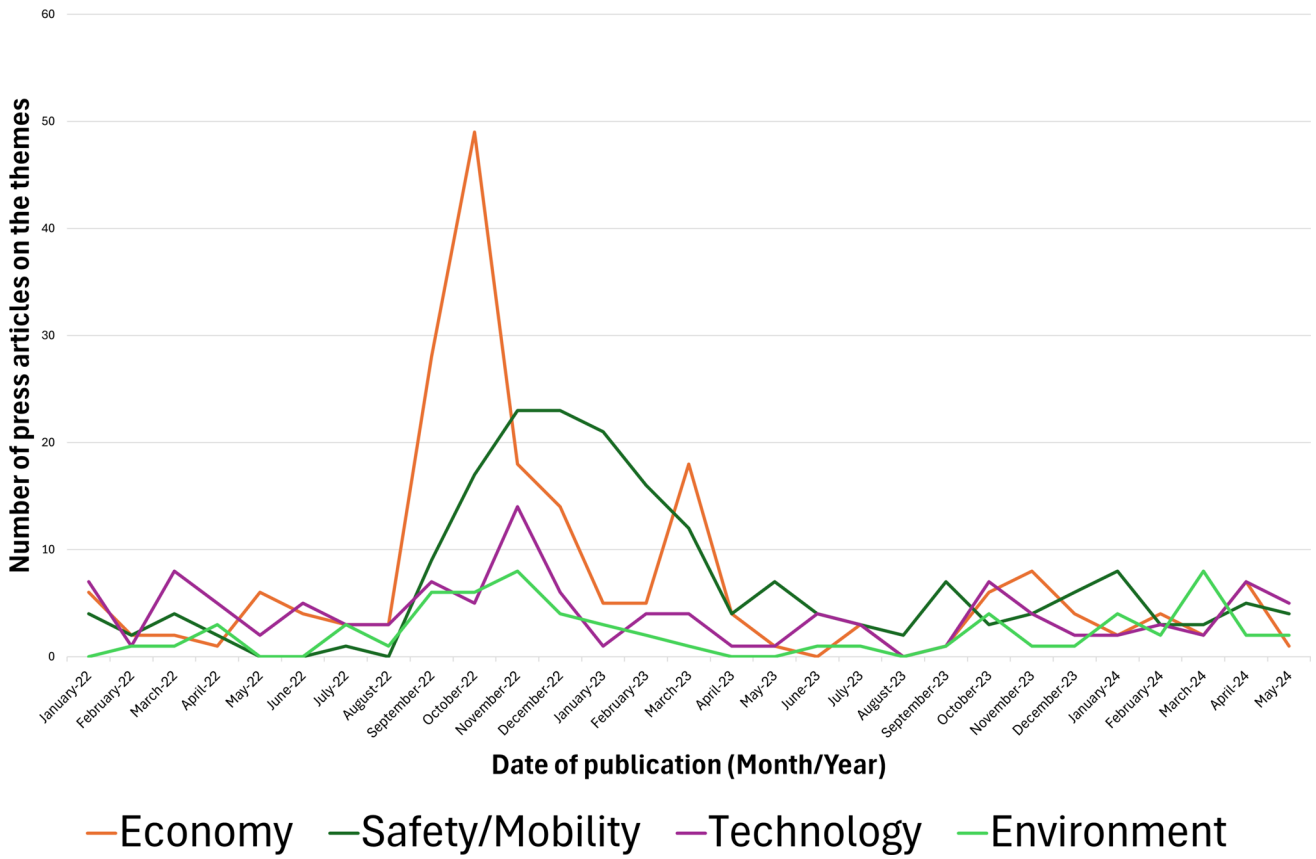

Fig. 2 Monthly evolution of media coverage (number of articles) of public lighting in French- and German-speaking Belgian press between January 2022 and May 2024, per theme

over the period 2012–2022 was 1.4%. The macroeconomic context (COVID-19 pandemic, floods in the summer of 2021, energy crisis, inflation) significantly influenced the growth rate and regional budgets [13, 25, 26, 158].

In 2021, the total energy consumption for municipal streetlights in Wallonia amounted to 197.1 million kWh, representing half of the municipalities' total electricity consumption [157]. This corresponds to €78.83 million (with a price of €0.40/kWh) annually paid by the Walloon municipalities [37]. In 2023, the cost of public streetlighting increased by 46% in the ordinary municipal expenses, with the municipalities advanced in the LED investments being less affected [13, 26]. This substantial investment in LED lighting infrastructure marks the initiation of a Kuznet's cycle [69].

Finally, energy expenditure reduction, in the form of extinction between 12 a.m. and 5 a.m. across the Walloon municipalities, is estimated by Duquesne [37] to yield annual savings of €34.68 million. Regional authorities promote such decisions through a dedicated circular [24].

4.3 Social dimension

Wallonia has 3.7 million inhabitants [146]. From a demographic perspective, the population is ageing [146]. From a social perspective, 25.8% of the population lives in a household at risk of poverty or social exclusion [67].

With regard to the sustainable management of the nocturnal environment, no synthetic information exists on the organisational field governing the nocturnal environment. Moreover, there is a paucity of information regarding the awareness and position of citizens in the region. Yet, according to Cornet and Touzain [28], French citizens generally do not strongly resist reductions in public lighting. Their support varies widely regarding the practical implementation, as noted by Beaudet et al. [11]. Based on a study in Flanders, Struyf [148] highlights conflicting values between environmental protection, crime prevention, and public fear of crime. She argues for science-based decision-making by local authorities on public lighting reduction. In Brussels, Farina et al. [53] find how unsafety at night limits the inclusiveness of the public space and impacts women's mobility strategies. Considering the cultural

proximity between Wallonia and France [96], and with the neighbouring regions of Belgium, a similar attitude may be expected among Walloon residents.

Several initiatives aim to raise awareness of the issue. The Ministry of the Environment of the Czech Republic [95] reports the organisation of the annual "Night of Darkness" event by ASCEN. Moreover, a call for projects destined for the municipalities is open until the beginning of 2024 with two aims: raising awareness of light pollution and designing dark ecological networks [145].

4.4 Technological dimension

The ageing public lighting infrastructure, primarily consisting of high- and low-pressure sodium lamps (HPS and LPS), is currently undergoing modernisation using LED technology [37, 85, 109].

LED technology, chosen for its energy efficiency, extended lifespan, remote control capabilities, adaptive intensity (*dimming*), potential presence sensors, and improved focus, facilitates dynamic artificial lighting adjustments based on time and activity frequency.

Nevertheless, LED technology introduces the risk of a rebound effect. From 2017 to the beginning of 2022, the total number of municipal lamps in Wallonia increased by 17 910, reaching 622 972. Of these, 2.4% were LED lights in 2017, and 27.3% in 2022 [37]. Moreover, there are technical limits to dimming, which are linked to the remanence of the lights. The drawback of more focused lamps is a higher risk of glare. Whiting et al. [159] warn against the implications on sustainable development of a longstanding trend, which consists mainly of improving the light infrastructure's fuel efficiency at the expense of the materials composing it. Furthermore, the use of LED lamps incurs a modification of the spectral composition of the artificial light emitted, affecting the wildlife [90].

Private actors based in Wallonia are engaged in research and development of lighting solutions with regard to light pollution. Examples of such research include that conducted by ENGIE Laborelec [47] and Schréder [133]. However, no specific project in Wallonia has been publicly shared.

4.5 Environmental dimension

Light pollution, defined as "excessive or obtrusive artificial light caused by bad lighting design" [55 p. 658], is an emerging concern with low recognition [88]. More precisely, Longcore and Rich [83 p. 191] define ecological light pollution as "artificial light that alters the natural patterns of light and dark in ecosystems".

Given that the effects of light pollution are not limited to a specific area and that no study on the ecological impacts of light pollution has been conducted in the Walloon territory, we have chosen to summarise the existing knowledge on the subject without reference to the specific Walloon region. We review the impacts of ALAN on ecosystems and structure our discussion around the SDGs, as reducing light pollution helps work towards more sustainability [152]. While our focus primarily concerns specific SDGs, we acknowledge that all are interconnected. Our approach seeks to address the most pressing issues identified, without undermining the broader objectives of the other SDGs, which remain integral to holistic sustainable development.

SDG 3 - Good Health and Well-being. The phototoxicity created by light affects human health. It induces retinal diseases and inhibits melatonin production. The hormone regulates the circadian rhythm and is a powerful antioxidant, a free radical scavenger, a regulator for both body temperature and the immune system, and a stabilising agent for tumours [23, 35]. Zielinska-Dabkowska [163] discusses the health impacts of artificial lighting, such as disruptions to sleep patterns and metabolic processes, which are directly related to human well-being.

SDG 11 - Sustainable cities and communities. According to Zielinska-Dabkowska [164], SDG 11 lacks attention to urban illumination and its effects. She highlights the need for in-depth, transdisciplinary research to foster sustainable urban development at night. A theoretical design framework has been proposed, comprising four iterative phases to aid stakeholders such as urban planners and architects. This framework provides a structured approach to effective lighting design in urban nighttime settings.

SDG 13 - Climate action. The mitigation of the negative externalities of ALAN primarily focuses on energy savings and reduction of carbon emissions [3, 64]. For instance, Kerem [73] investigates energy efficiency and carbon emission reduction strategies for the outdoor lighting system of Avşar Campus, Kahramanmaraş Sütçü İmam University, Turkey. Seven energy-saving strategies were developed to address this, focusing on dimming methods, optimising operating times, and upgrading to more efficient lighting technologies. The most effective strategy could reduce energy consumption

by 81.656% (547 418 MWh/year), save 180 599 tons of CO_2 annually, and achieve cost savings of €49 268 per year. LEDs are known for their low operational energy consumption [3, 64], but it is crucial to address the embodied energy, that is, the total energy required for their production, to fully realise the benefits of sustainable energy solutions, which can have significant environmental consequences [149]. In their life-cycle analysis (LCA) of outdoor LED luminaires, Lozano-Miralles et al. [84] identify the extraction of materials (aluminium, steel, plastic, glass) and the depletion of resources linked with the transportation of the components of the luminaires as the most significant environmental impacts, and propose LCA as a tool for eco-design. This suggestion should also support SDG 12, which aims to ensure sustainable production and consumption.

SDG 14 - Life below water and SDG 15 - Life on land. ALAN threatens the wild at all levels (from genes to ecosystems) and throughout all stages of life [51, 143]. Light impacts the physiology and behaviour of wildlife and incurs modifications in their migration, foraging, and reproductive habits. Moreover, luminance creates attraction, repulsion, or disorientation [56, 83, 120, 143]. Peregrym et al. [119] synthesise the literature on the impacts of ALAN on various taxa. Sanders et al. [129]' research highlights significant implications of ALAN on the natural environment, emphasising its widespread effects on both nocturnal and diurnal species and the need for routine mitigation. The study reveals that even low lighting levels can have marked biological impacts, affecting organism physiology and behaviour, including hormone levels and daily activity. The research also notes potential changes in community composition due to ALAN, and echoes concerns about its effects on human physiology and psychological well-being. Finally, artificial lighting provokes the disruption of ecological systems [83] and affects species composition within their natural ecosystems [32]. More specifically, evidence shows that LED technology, whose spectrum can be partly found in the blue wavelengths, affects more species than sodium lighting. Furthermore, the authorities have recourse to partial switch-off of public lights to reduce their energy expenses and carbon footprint. Little evidence addresses the impact on the biodiversity of this partial switch-off (or dimming) of public lighting [90].

With regards to evolving scientific knowledge, the Ministry of the Environment of the Czech Republic [95] mentions the research activities undertaken by the SPW-DNF, which are focused on understanding and mitigating the impacts of light pollution on biodiversity. Furthermore, this report underscores the absence of any Dark-Sky Area in the region.

4.6 Legal dimension

Although the State is sovereign to establish the legislation, the Ministry of the Environment of the Czech Republic [95] reports no legislation on light pollution in Belgium, and therefore in Wallonia, except for standards. These standards are the norms NBN L 18-004 and EN 13201. The good practices of the Belgian Institute for Lighting [66] are observed. Local initiatives propose good practices, guidance, and charters [7].

4.7 Summary of the PESTEL analysis

Figure 3 summarises these developments into six dimensions, further categorised into three groups based on their potential impact on advancing sustainable management of the nocturnal environment in Wallonia.

5 Discussions - night as an interdisciplinary field

Hölker et al. [64] and Kyba et al. [78] advocate for considering the night as an interdisciplinary research field. Kyba et al. [78] propose "nyctology", the study of nighttime matters, to counter the notion of fragmented night research. Collaborative practical and research efforts can help mitigate the adverse effects of light pollution while preserving essential services provided by artificial lighting. Examining Wallonia's case offers a comprehensive perspective. It serves as a model for implementing recommendations from previous fragmented studies, gaining insights from other countries' experience, and highlighting areas for further exploration. This approach helps us grasp these findings' broader implications and practical applications.

Through the lens of the Walloon case, we identify potential threats and opportunities. By leveraging fragmented international research and initiatives, we identify practical solutions and points of attention for their implementation in Wallonia and highlight areas for further exploration.

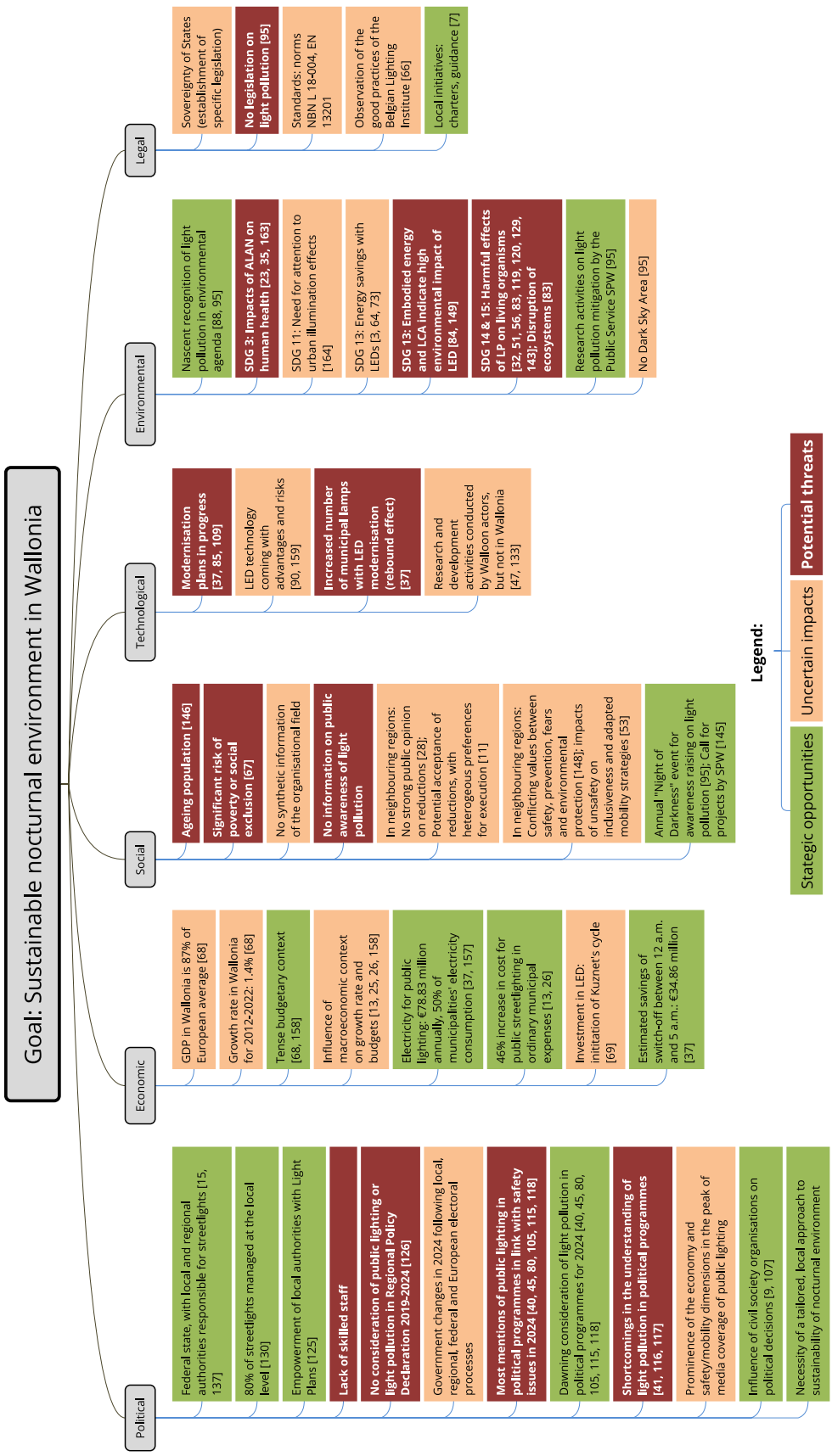

Fig. 3 Summary of PESTEL dimensions of the macro-environment of the nocturnal environment in Wallonia

5.1 Strategic opportunities, uncertain impacts and threats to sustainable transition

Potential opportunities for the transition We identify the strategic opportunities that organisations could seize for a sustainable nocturnal environment (in green in Fig. 3). In the political dimension, the local scale of responsibility for public lighting and territorial matters presents an opportunity. The global discussions can be made real and practically implemented in local contexts [135]. This enhances the suitability of solutions to local contexts and, therefore, the efficacy of the measures taken. This can be reinforced by the implementation of appropriate lighting master plans [27, 164]. The consideration of light pollution mitigation measures in political programmes is an opportunity, as Morgan-Taylor [101] argued that voters must grasp the value of these measures, and policymakers must consider them worthwhile. The involvement of civil society is crucial for the dissemination of information and the formulation of more informed decisions, as well as for facilitating collaborations with other actors [92]. In the economic dimension, the budgetary context, the significance of expenses dedicated to public lighting, and the increase in energy prices could influence the authorities to implement reduction policies, which are expected to yield annual savings of €34.86 million [37]. In the social dimension, calls for projects and annual events dedicated to awareness-raising activities represent opportunities that can be reinforced with citizen science projects [76, 77] or material issued by international associations, for instance DarkSky International [30]. In the environmental dimension, the increasing knowledge and recognition in environmental agendas present a positive opportunity, particularly if there are research activities in the region. In the legal dimension, existing local initiatives could form part of the guidance suggested by Morgan-Taylor [101].

Uncertain impacts on the transition. The factors whose impacts on sustainability remain uncertain are in orange in Fig. 3. In the political dimension, the government changes of 2024 have an uncertain impact on the sustainability of the nocturnal environment, as it depends on the coalitions and agreements among political parties. The prominence of safety topics in the press, as confirmed by Green et al. [59], has an uncertain impact. The authors identified deep anxieties related to darkness, but the population did not notice reductions in lighting. In the economic dimension, the influence of underlying economic variables should be better understood [55]. The impact of the initiation of a Kuznet's cycle [69] depends on their initial consideration of sustainability issues and the potential to adapt the infrastructure. In the social dimension, information from neighbouring regions should be tested and compared with Wallonia. Therefore, their impacts on the region remain uncertain. Furthermore, the organisational field and its actors should be modelled in order to gain a deeper understanding of their role in the sustainable transition. In the technological dimension, how the advantages and risks of LED are balanced is uncertain. Research and development activities are performed with the expertise of Walloon actors, but not in Wallonia: their future projects in the region are unknown.

In the environmental dimension, the energy savings of LEDs are an opportunity for SDG 13. However, the extent to which these savings are offset by the rebound effect is uncertain. If implemented effectively, the design framework proposed by Zielinska-Dabkowska [164] could enhance the efficacy of urban lighting design. Finally, Dark Sky areas increase awareness of light pollution and effectively reduce the pollution [92, 147]. Nevertheless, Morgan-Taylor [101] cautions against the assumption that the establishment of Dark Sky areas ensures the protection of the night sky in these reserves, thereby negating the need for similar protection in urban settings. In the legal dimension, the impact of state sovereignty is contingent upon the manner in which regulations are created, adapted, and implemented. Adherence to the standards and best practices of the National Lighting Institute could be a potential opportunity, contingent upon the lighting industry and civil society groups substantially informing bolt-on regulation [101].

Potential threats to the transition We now focus on the dimensions in the macro-environment that could threaten the sustainable transition of the nocturnal environment (in red in Fig. 3). In the political dimension, the absence of consideration of light pollution in the Regional Policy Declaration demonstrates a lack of consideration of the problem. The threat could be eradicated if the issue were explicitly considered in the Declaration after the 2024 elections. The lack of lighting professionals in the municipalities represents a threat, as these are important actors [135]. A narrow focus on safety concerns in political agendas could impede the comprehensive and sustainable management of biodiversity. This could be further compounded by deficiencies in the comprehension of light pollution, which is perceived as a problematic issue by Schulte-Römer et al. [135]. In the social dimension, the ageing population, poverty, and social inclusion are concerns that, if not adequately addressed alongside environmental risks and urban planning, pose substantial threats [61, 141, 151]. The absence of information on the actual awareness of light pollution among the general public, which Schulte-Römer et al. [135] described as general and problematic, could potentially impede the effectiveness of targeted education initiatives. In the technological dimension, the modernisation plans may present a potential threat. Indeed, Schulte-Römer et al [135] cautioned against a low priority being assigned to light pollution in lighting projects

and the installation of LED lighting that fails to consider its harmful effects. Ebbensgaard [42] warns against the uneven geographical distribution and repercussions on nocturnal social life linked with the LED installation. Moreover, the risk of the rebound effect represents an additional threat [18]. In the environmental dimension, the potential adverse effects of ALAN and the production of LED lighting, if not adequately addressed through appropriate design and management, could impede the sustainable development of the nocturnal Walloon environment. In the legal dimension, the absence of dedicated legislation on light pollution represents a significant challenge. As identified by Morgan-Taylor [101], this represents the most effective regulatory tool for controlling light pollution.

5.2 Priority leads for future actions

We suggest pivotal leads that could shape future actions towards sustainable nightscape management.

Political initiative and willpower Local authorities play a central role in decision-making and are the final deciders for the light plans. However, they have shown limited interest in light pollution, with varying levels of commitment to limiting their impact on their SETS. Our analysis of political programmes aligns with Mosser [102]'s argument that election promises on public lighting aim to reduce crime and insecurity. Hence, training on light pollution is needed across municipalities. Nevertheless, there is a rising expectation from citizens for policymakers to address light pollution [28]; and the Walloon policymakers are increasingly considering the issue, which joins the conclusions of Zimmerman [165]. Notwithstanding, Green et al. [59] indicate that trust in authorities to work in the best interest of the communities is fundamental.

With regards to nightscape protection, the most broadly used policy instrument is the dark sky area (promoted by the International Dark-Sky Association, among others). Such endeavour involves the cooperation of multiple stakeholders at local and regional scales (astronomers, environmentalists, heritage preservationists, politicians and businesses), and requires public and political support. While these actors have various interests, Meier [92] found them to broadly align or complement each other to generate synergies, resulting in harmonious collective work. Yet, the more populated the area, the more political the case becomes. The authors anticipate more friction and negotiation between the values of darkness and light. As the organisational field of the nocturnal environment in Wallonia has not been formally modelled, such an endeavour could allow for a better understanding of the actual collaborations and negotiations among actors.

Another interesting endeavour is Prague's conceptual and systematic approach, consisting of a Lighting Master Plan, renewal plan and standards, to managing public and architectural lighting [95].

Financial support Ożadowicz and Grela [113] report that street lighting systems consume about 40% of the total electricity of a city. Indeed, Allcott and Rogers [4] estimate street lighting's share of municipal electricity consumption to be between 30-50%. This corresponds to the observations in Wallonia. Furthermore, as reported by Meyer et al. [94], the World Bank emphasises that energy costs for street lighting often constitute the second-largest budget item for many municipalities, exceeded only by payroll expenses.

However, the European Union (EU) has developed strategies to bolster energy resilience, focusing on supply and demand. Current policies target energy use in households and businesses, mainly indoor lighting, but neglect the impact of outdoor lighting, like municipal street lighting, on total energy consumption. This is highlighted by Meramveliotakis and Manioudis [93].

The financial mechanisms could be adapted to comprise sustainable requirements. In this regard, Morgan-Taylor [101] identified a lack of recent economic studies on the costs of light pollution. Performing such an analysis in Wallonia would allow the recognition of financial incentives.

Dark sky areas could be economically interesting for the region. Mitchell and Gallaway [98] evaluated the economic impact of dark sky tourism on the Colorado Plateau (USA). The study's findings indicated that dark skies have the potential to generate increased revenue from tourism, create employment opportunities, and facilitate year-round tourism, which is not limited to peak periods.

Awareness-raising for citizens and municipalities, and social considerations The *safety-public lighting* couple is a long-standing relationship [55, 102]. Indeed, emotional fear of darkness induces residents to oppose regulation that would decrease ALAN [101]. The use of LED technology appears to influence the emotional response. For instance, Kaplan and Chalfin [70] found that individuals exposed to an image of a street with enhanced LED lighting felt less fearful about spending time outdoors compared to those who saw the same street with dim yellow lighting. However, there were no significant differences in how they intended to use the public space. Besides, issues are raised on the link of public lighting with (fear of) crime, road safety, mobility, and inclusiveness of the public space [53, 78, 148]. In their study of the English and Welsh population, Green et al. [59] identified four key public concerns linked with reductions in street

lighting: road safety, mobility, fear of crime, and access to the dark sky. However, despite these reductions going unnoticed in practice, the authors elicited deep anxieties related to local governance, darkness, and modernity regression. Such links are contingent upon the interplay between location, expectations regarding illumination, and the degree of confidence placed in authorities.

Furthermore, Schulte-Römer et al. [135] and Willmer [161] confirm an overall lack of public awareness of the consequences of ALAN, which represents an obstacle to mitigation measures. Heightened ecological knowledge empowers the integration of biodiversity concerns into sustainable transition reforms [140]. Anticipating citizens' reluctance could hinder political initiatives [11]. Participatory democracy can usefully involve informed citizens. The level of awareness about light pollution among the Walloon population needs to be clarified, as well as their acceptance of measures for a sustainable nocturnal environment.

Still, local and large-scale campaigns could educate citizens about light pollution. For instance, DarkSky International [30] proposes diverse initiatives and materials to support educational activities. Through its DarkSky Approved programme, the association issues certifications for lighting products, design, outdoor sports lighting projects, lodging and initiatives for turtle preservation [31]. Citizen science projects such as the "Nighlights" and "Loss of the Night" apps [76, 77], and conference series such as Artificial Light at Night Conference [8], among other initiatives, increase awareness of light pollution.

The media should amplify this message, as Harring et al. [62] show that their coverage deepens public environmental concern. Morgan-Taylor [101] suggests repositioning the issue of light pollution around aspects that better resonate with the population, hence striking a balance between legitimate but competing needs for ALAN and reduction of its adverse effects. Moreover, Schulte-Römer et al. [135] posit that education is essential, and that the engagement of local stakeholders and residents, whether experts or not, in debates in the frame of concrete projects represents a good starting point.

Overall, Schulte-Römer [134, p.186] proposes the concept of "cosmopolitics of dark skies", which grasps the "multiplicity of perspectives, confusing or even contradictory facts, incommensurable values, and incompatible views in order to struggle for "good" solutions and protect our cosmic commons." According to the author, this perspective calls for negotiations. Beyond the habit of resorting to lighting as a routine procedure or a symbol of modernity, it allows reconsidering the practices based on contrasting values, new insights into darkness, and the latest available technologies [134].

Environmentally friendly technological developments Although the modernisation plans are ongoing, it is crucial to continue addressing the environmental impacts of LED lighting. In this sense, Morgan-Taylor [101] suggests prioritising the elements most relevant to the population's realities, and Schroer et al. [132] advocate coherent strategies applied to all landscapes. In addition, Schulte-Römer et al. [135] identify the promotion of best practice lighting projects at the local level to be an approach both lighting professionals and experts agree upon.

Schroer et al. [132] identified a lack of coherent strategies across regions, which could create biodiversity corridors. The latter is a framework advocated by Challéat et al. [22] to mitigate the effects of light pollution on biodiversity. Furthermore, the LED technology evolves rapidly and should include mitigation measures such as intensity reduction, and control of radiation geometry and colour [132]. The DSOs can provide technical expertise to support sustainable design and planning.

Moreover, building on the advantages of LED technology, Dey and Thakurta [34] develop a cost-effective, energy-efficient street lighting system that harnesses the synergy of wireless sensor networks and dimmable LED lighting. This system, governed by a microcontroller, dynamically adjusts illuminance levels to optimise energy consumption, reduced electricity costs, and significantly lowers CO_2 emissions. Umamaheswari [155] further incorporates an advanced architecture comprising sensors, Wi-Fi and GPS modules, Cloud Storage, and an Internet Gateway, allowing for automated control and remote monitoring via a Web Application Interface. Additionally, the system's intelligent design adjusts the intensity of streetlights based on sunlight and vehicle movement. This further contributes to its energy efficiency and functionality in smart cities [89, 100]. Nonetheless, Schulte-Römer et al. [135] acknowledge the prevalence of smart lighting projects and the concurrent dearth of initiatives that effectively integrate sustainable approaches.

Anyway, the modernisation of the infrastructure with LED is not a panacea. Ebbensgaard [42] found that light clutter and bleed contribute to nocturnal atmospheres that users perceive as safe. Acknowledging these benefits is necessary to guarantee lighting that reduces the impacts on wildlife while responding to social needs.

Finally, autonomous vehicles represent a hope for reducing light pollution and striking a better balance between functional lighting needs and environmental values regarding darkness. Indeed, the design of future autonomous vehicles opens the opportunity to reexamine the reasons and ways to light nightscapes. This would require a *higher-order* level of automation, social, institutional and regulatory changes, and systems necessitating little to no light for nocturnal

navigation, for instance the combination of *light detecting and ranging (LiDAR)* technology and GPS. The consequences of such a transformation could result in the creation of more convivial urban spaces and a greater focus on pedestrians and cyclists in the context of urban planning for lighting [147].

Legal recognition Light pollution regulation in Wallonia is currently lacking, a concern shared at the EU level where standardised legislation is absent, although the EU has the potential for proposing binding obligations [132, 160]. Hence, the legal framework significantly varies across Europe [95, 101, 132]. Morgan-Taylor [101] confirms the modest consideration of light pollution in legislation worldwide.

The EU provides directives, which individual member states then regulate independently. The European Committee for Standardisation issues general standards on public lighting (e.g. standard EN 13201). Schroer et al. [132] argue that this standard, while addressing minimum brightness levels, lacks consideration for ecological impacts and establishing maximum brightness limitations. In addition, the EU Green Public Procurement suggests maintaining light levels "as low as reasonably achievable" and advises for certain light temperatures [36].

In countries where light pollution mitigation measures are implemented, Widmer et al. [160] identify four strategies: strict metrics, education, law inclusion, or formulation with astronomers. Morgan-Taylor [101] advocates for a multi-pronged approach, which combines dedicated anti-light pollution legislation with complementary regulations integrating light pollution concerns into existing laws initially not dedicated to the issue, and coupled with robust guidance, preventative measures, educational initiatives, and a focus on design that minimises the need for future regulations. This is confirmed by Schroer et al. [132].

Schroer et al. [132] identify shortcomings in the existing legislations. These include unaddressed adverse effects on species and landscapes not specifically protected, potential underestimation of impacts on some species due to current criteria, and difficulties in proving harm, detecting violations, and applying existing laws to light pollution. Moreover, the authors recognise the available legal tools as incompatible with ALAN, as they should incorporate precise technical requirements. In addition, although regulations frequently prioritise the preservation of the night sky, this focus can impede public awareness and political support [101]. This highlights the inherent interconnectedness of regulation with social and political dimensions. Wallonia could gain from anticipating these shortcomings in developing light pollution legislation.

Nevertheless, while standards and regulations promote homogeneity and uniformity, designers can respond to them with nuance in their interpretation. If designers were empowered to challenge these metrics, they could transform regulations into frameworks for sustainable lighting. This shift would allow for luminous differentiation and darkness preservation, nurturing socially and environmentally responsible lighting solutions [43].

5.3 Research challenges

The scientific community may have influence on all PESTEL dimensions. Therefore, we provide concise research recommendations to guide future efforts under the nyctology paradigm. These suggestions update and extend the research agenda proposed by Hölker et al. [64] and should support implementing the outlined lines of action.

Governance and policy-making (Political and legal concerns) Further research is needed to investigate the optimal governance structure for the public lighting infrastructure [3, 97]. Comparing policies on light pollution with those of other countries, as suggested by Hölker et al. [64], and measuring the overall efficiency of these policies, including economic, social, and environmental impacts, is essential. Moreover, effective regulation necessitates continuous adaptation to incorporate evolving research findings across all dimensions [101].

Economics To inform effective policy decisions, Morgan-Taylor [101] pleads for recent and robust economic analysis to quantify the financial and environmental costs associated with light pollution. Further understanding the economic factors of light pollution is twofold: first, the underlying economic variables explaining light pollution [55]; second, the valuation of its externalities, including the rebound effect [18]. Conducting cost-benefit analyses for light pollution mitigation policies, determining citizens' willingness to pay for such policies, and performing life-cycle cost analyses of proposed solutions should be implemented [99]. Additionally, identification and valuation of the ecosystem services offered by ALAN, the darkness, or lost due to light pollution, should be performed and further extended to complete species ranges [75].

Social and technological dimensions Szewrański and Kazak [151] emphasise the importance of socio-environmental vulnerability assessment for sustainable management, highlighting the complex interactions between social, economic, and environmental systems. They discuss the need for adaptive strategies in response to challenges such as urbanisation

and demographic shifts. The research identifies a growing academic interest in this area, underscoring its significance for future management and policy-making initiatives.

Sobczak et al. [141] explore the impact of environmental hazards on the ageing population in Poland while Grey et al. [61] discuss the relationship between ageing populations, the built environment, and urban ecosystems, focusing on how cities can adapt to serve their ageing residents better. They outline the concept of cities as complex adaptive systems and social-ecological systems. Key aspects include designing urban spaces that enhance accessibility and safety, and integrating natural elements to improve overall well-being for seniors. Indeed, public lighting is crucial for ensuring safe navigation and accessibility for the elderly, particularly those with visual impairments. Investigating how public lighting can be optimised to support the mobility and safety of older adults is important for urban planning. Further research could lead to improved guidelines and urban designs that promote independence and well-being among the ageing population.

Moreover, infrastructure is often lacking in lower-income areas. Future research could focus on the long-term effects of optimal lighting technologies and designs on community health, economic development, and environmental impacts to further explore the impact of public lighting on lower-income communities.

Adopting the technology should be further studied, along with integrating social interactions with intelligent street lighting [3]. Moreover, local citizens' acceptance of public lighting reduction plans must be tested [11].

Finally, Entwistle and Slater [48] found the institutionalised differentiation between technical and aesthetic lighting to yield an impoverished space for the *social*. They elucidate the complex negotiations over this space of the social that sociologists must access to perform the essential task of inventing the social.

Environmental considerations Quantitatively measuring the unsustainability of public lighting and valuing the potential gains of suggested policies is necessary. As a first approximation, we evaluate a total of 5.5 million insects that could be preserved every night in Wallonia. We base this calculation on the estimations of 150 insects dying every night (in neighbouring Germany, in the summer) per light point [46], and of 37 320 municipal light points identified as unnecessarily disturbing biodiversity [144]. Refining this estimation and examining ALAN's interaction with other environmental pressures through quantitative studies is thus essential [129]. Moreover, Schroer et al. [132] emphasises the absence of a clear light intensity threshold below which no harm is caused. Meier [92] requests measuring the effectiveness of dark sky areas for reducing light pollution.

Urban Lighting Masterplan [27, 164] addresses multiple outcomes, including environmental protection, human health, and public safety. These plans aim to reduce light pollution while ensuring adequate illumination for safety and security. They advocate for using adaptive lighting technologies and minimising lighting to mitigate impacts on wildlife [56, 83, 120, 143]. Additionally, they promote using lighting spectra that are less disruptive to human circadian rhythms [23, 35] and to incorporate adaptive technologies, such as smart lighting systems, that balance safety and environmental concerns [64].

Establishing clear policies and regulations for urban illumination should include guidelines on acceptable light levels, fixture designs to minimise skyglow, and regular assessments to ensure compliance with sustainability goals [83]. Authorities sometimes resort to partial switch-offs or dimming of public lights to reduce energy expenses and carbon footprint. However, little evidence addresses the impact on biodiversity of these measures [90].

Data collection The identified research areas require accurate data collection, including public opinion on street lighting, the night, and policy acceptance. Data on population mobility, historical road accident records, and crime rates should be accessible for analysis. Future analysis should incorporate urban big data, as suggested by Liu et al. [82], to further support the development of smart cities. Additionally, data on ecosystem services and cost functions should be collected for complete ranges of species [75].

6 Conclusion

This study analysed the Walloon nocturnal environment through a SETS lens. The case of Wallonia presents a unique opportunity to examine the challenges of balancing sustainability goals. Modernisation efforts for public lighting highlight the need to optimise LED implementation while mitigating light pollution and proposing adequate strategies in a context of energy crisis.

The employed PESTEL framework provides a comprehensive understanding of the macro-environmental factors influencing the region's nocturnal sustainability. This approach offers valuable insights for policymakers, planners,

and civil society to inform decision-making. This framework is well-known in management, which could ease case replication.

The analysis identified key considerations for achieving a sustainable nocturnal environment in Wallonia. Public awareness campaigns and well-designed legislation are essential components. Additionally, balancing social and environmental objectives through effective light and darkness management strategies remains critical. This study further contributes by incorporating international research perspectives and highlighting areas for further investigation.

Future research holds promise for advancing understanding in three main directions. First, a deeper analysis within each PESTEL dimension, potentially incorporating econometric models or sentiment analysis for instance, could provide more nuanced insights. Second, replicating this case study in other regions would facilitate comparative analysis and knowledge sharing. Finally, applying the regional SETS approach to local contexts could offer a user-centric, bottom-up perspective, enabling a more accurate balance between the social and ecological aspects of nocturnal light management, and balancing the needs for darkness and light.

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Author contributions Conceptualisation, Methodology, Visualisation: EB, SH & SL; Writing - Original Draft: EB, Review & Editing : EB, SH &SL, Supervision: SL. All authors have read and agreed to the published version of the manuscript.

Data availibility The relevant materials can be obtained from the references below.

Declarations

Competing interests The authors declare no competing interests.

Appendix

Method for thematic sorting of media coverage

The articles were sorted based on the following lexical fields (with keywords translated in English, for ease of understanding): economy (bill, economy, cost, budget, euro, investment, expense, rate, subsidy, profitability, €, grant, finance), safety and mobility (safety, prevention, crime, surveillance, vandalism, theft, accident, dead, death, injury, knock over, pedestrian, risk, delinquent, police, protect, danger, assault, mugging, burglary, cyclist, robbery, knock down, mobility, incivility, collision, victim, disorder, bicycle, incident), urban planning (planning, infrastructure, work, lamp, pole, renovation, road, highway, space, equipment, work site, failure, defect, solved, adaptation), energy (crisis, energy, consumption, electricity, efficiency), technology (LED, technology, smart, control, innovation, sensor, detector, replace, tomorrow, remote control, modernisation, intensity), local governance (politics, decision, consultation, survey, college, council, municipality, management, administration, authority, collectivity, regulation, burgomaster), environment (pollution, light pollution, fauna, flora, bat, toad, frog, wolf, corridor, environment, health, biodiversity, bird, insect, Night of darkness, nature, climate, animal, star, ecology), legislation (decree, order, law, legal, charter), miscellaneous (Christmas, holiday season, tinsel). All derivatives were included in the search. The articles related to no field or more than four fields were manually verified based on title and abstract, and deleted if unrelated to public lighting. A second manual verification of the title and abstract of the remaining articles located unrelated articles.

Results of thematic analysis of media coverage

Figure 4 represents the evolution of media coverage of public lighting, as measured on a quarterly basis. The thematic analysis provides the number of articles referencing each theme during the specified period. A single press article may reference multiple themes.

Figure 5 represents the evolution of media coverage of public lighting, as measured on a monthly basis.

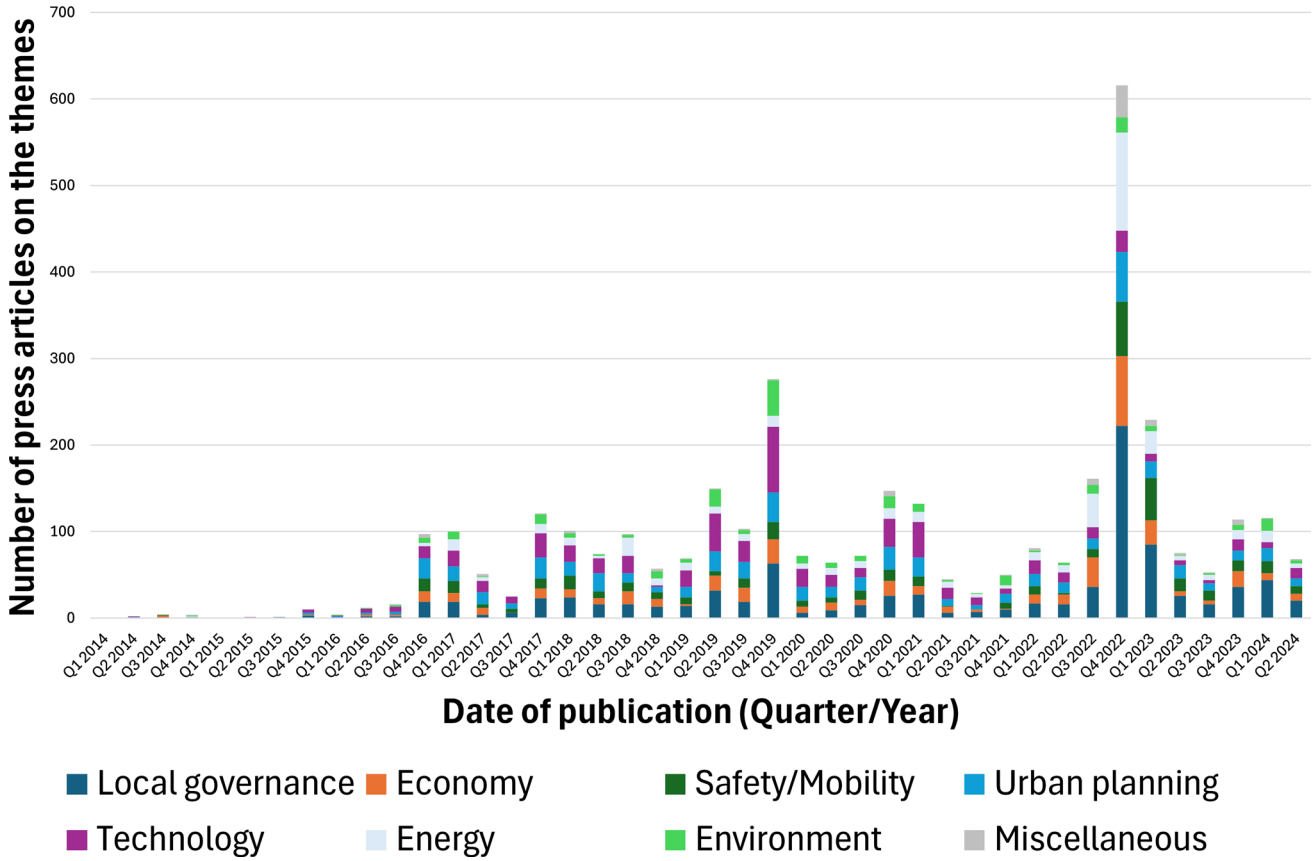

Fig. 4 Quarterly evolution of media coverage of public lighting in French- and German-speaking press between January 2014 and May 2024, per theme

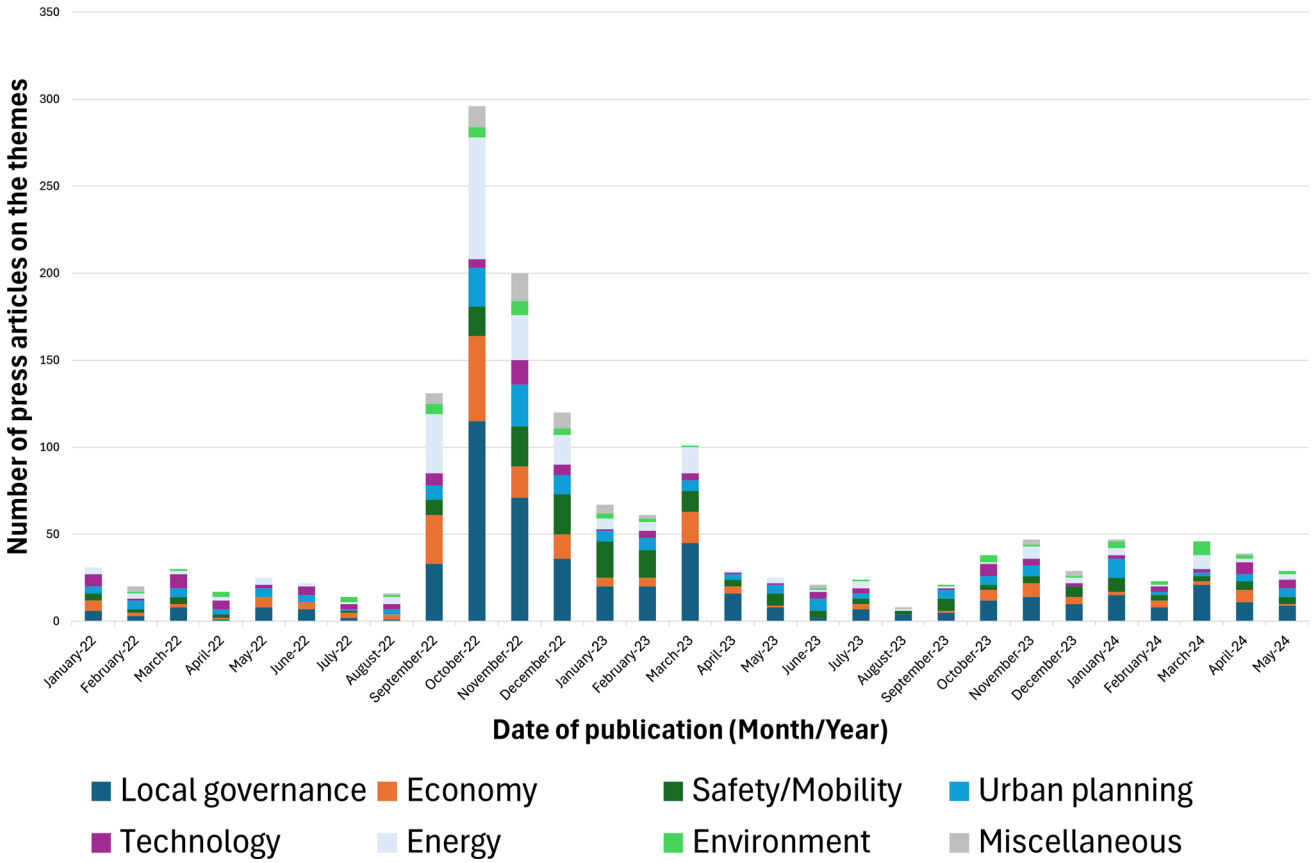

Fig. 5 Monthly evolution of media coverage of public lighting in French- and German-speaking press between January 2022 and May 2024, per theme

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