

Review

The Impact of Daylight Saving Time on the Energy Efficiency of Buildings: A Bibliometric and General Review

Ivo Araújo ¹, Leonel J. R. Nunes ¹, David Patíño Vilas ² and António Curado ^{1,*}

¹ proMetheus, Unidade de Investigação em Materiais, Energia e Ambiente para a Sustentabilidade, Instituto Politécnico de Viana do Castelo, Rua da Escola Industrial e Comercial de Nun'Alvares, 4900-347 Viana do Castelo, Portugal; ivo@esdl.ipv.pt (I.A.); leonelnunes@esa.ipv.pt (L.J.R.N.)

² CINTECX, University of Vigo, Lagoas-Marcosende, S/n, 36310 Vigo, Spain; patinho@uvigo.gal

* Correspondence: acurado@estg.ipv.pt

Abstract: The absence of standardized time zones has profound implications, influencing social, economic, and energy dynamics. It also disrupts personal aspects, such as sleep patterns and family routines. One specific dimension of this issue is the transition to daylight saving time (DST), which entails shifting between standard time (winter) and daylight saving time (summer). This practice has sparked global debates due to its varying impacts across regions and sectors. Although DST primarily aims to optimize energy consumption by leveraging natural daylight, much attention has focused on its broader societal effects. However, the energy performance of commercial buildings under DST remains an underexplored yet equally significant area. This article presents a literature review to critically evaluate the effects of the winter-to-summer time shift on commercial buildings, concentrating on three key factors: energy consumption, where seasonal variations in lighting, heating, and cooling demands may alter anticipated energy savings; occupant thermal comfort, as time changes can disrupt the circadian rhythms of building occupants, impacting productivity and well-being; and operational considerations, as building systems like HVAC and automated controls must adjust to shifting daylight schedules. Accordingly, this review seeks to offer a comprehensive understanding of how the winter–summer time transition affects commercial buildings by analyzing energy consumption patterns, occupant comfort levels, and operational challenges. In doing so, it contributes to optimizing building management practices under varying daylight conditions to enhance energy efficiency and occupant satisfaction.

Keywords: energy efficiency; daylight save time; energy management; sustainable campuses



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1. Introduction

The transition between winter and summer time, commonly known as daylight saving time (DST), involves setting clocks forward in the spring and back in the autumn, with the initial aim of saving energy by extending daylight hours. Although the overall energy-saving advantages of daylight saving time (DST) have been extensively examined, its particular impacts on service buildings—such as offices, schools, hospitals, and other facilities—remain inadequately known and require additional investigation. The potential impacts on service buildings, ranging from energy consumption and lighting, HVAC systems, operating costs, human behavior, and productivity to maintenance and scheduling, are not well discussed, so addressing this knowledge gap could inform policy decisions and optimize building management practices during seasonal time changes.

The debate surrounding DST has largely centered on its societal and residential energy impacts, yet its effects on commercial buildings remain insufficiently understood despite their substantial contribution to national energy consumption. Commercial buildings, including offices, schools, and hospitals, account for a significant portion of energy use due to their reliance on lighting, heating, ventilation, and air conditioning (HVAC) systems, all of which are influenced by daylight availability and occupancy schedules. This study addresses this gap by examining how the biannual time shift impacts energy efficiency, occupant comfort, and operational management in these settings. By focusing on commercial buildings, we aim to provide actionable insights for building managers and policymakers, contributing to the broader discourse on DST's efficacy as an energy-saving measure.

In most European countries, the shift to DST has a considerable impact on the distribution of daylight hours. In particular, the clock adjustment has the rather contradictory effect of making nights longer and days shorter. The change in social time in relation to solar time, which causes a discrepancy with natural daylight patterns, could have an impact on this observation. Due to Europe's geographic location, the effects of summer may be more evident because natural daylight hours already show notable seasonal variations. As a result, some important issues need to be addressed, primarily the perception of night and day length, the energy implications, the behavioral and health effects, and the regional and seasonal effects [1].

The time change from summer to winter (summertime back to standard time) has been the subject of widespread debate, with opinions divided on its benefits and drawbacks. The different perspectives reflect different priorities such as energy savings, public health, economic impact, and societal well-being. Arguments in favor of the time change point out that, in terms of energy savings, the original rationale for summertime was to save energy, in particular, to reduce the need for evening lighting; however, there appears to be a modest reduction in energy consumption for lighting and cooling during the summer months, although the effect in winter is less clear. The results presented by Verdejo et al. for Chile indicate that the time change leads to a marginal reduction in residential electricity consumption, but that this reduction is not homogeneous across the Chilean territory [2]. This finding reflects the complexity of the effects of summertime, which can vary according to regional, climatic, and behavioral factors. According to the author, this reinforces the need to rethink this practice and evaluate alternatives that optimize energy use and reduce negative impacts on the population. Still on the same approach, in the study by Mirza and Bergland, the effect of DST leads to an average annual reduction in electricity consumption of 519 GWh in southern Norway and 882 GWh in Sweden [3]. These reductions translate into annual financial savings of EUR 16.1 million in southern Norway and EUR 30.1 million in Sweden. According to the authors, these savings are significant for countries with high electricity costs and dependence on limited natural resources as these savings can be redirected toward investments in energy efficiency or renewable energy infrastructure. Sweden shows the largest savings, both in GWh and in euros, probably due to differences in energy consumption patterns, tariff structures, or how summertime affects natural light availability. Similarly, the study by Ahuja and SenGupta [4] highlights that the effect of DST on reducing electricity consumption is not uniform throughout the day. In the two regions of India analyzed, the following was observed: small but significant reduction in morning consumption. Although DST often results in greater darkness in the morning, the impact on electricity consumption is moderate. This may be due to efficient consumption practices or to the fact that many morning activities take place at times when natural light is still available. The greatest savings occur at night, when longer daylight hours would significantly reduce the need for artificial lighting and possibly heating in milder climates. This effect is more pronounced because of the coincidence between the periods of

highest human activity and the availability of natural light [4]. Accordingly, the Flores and Luna research [5] estimates that the energy savings attributed to DST amount to 0.5% of total electricity consumption. The 0.5% savings reflect a real but limited reduction in total electricity consumption, so DST alone may not be a significant tool for addressing large-scale energy challenges [5]. On the other hand, they note that the effect of summertime varies over the period it is in effect, which can be influenced by changes in human behavior (e.g., gradual adjustment to new routines); and seasonal and climatic factors, such as variations in day length and average temperatures. The authors point out that greater savings can be achieved on days with greater overlap between human activity times and daylight hours. They conclude that the usefulness of DST should be assessed in conjunction with other policies to maximize energy and economic benefits.

In terms of public safety, more daylight in the evenings during the summer months is thought to reduce road accidents and improve safety, and the return to standard time in winter aligns waking hours more closely with sunrise, potentially improving visibility and safety in the morning. In terms of seasonal adaptation, the time change takes account of natural seasonal variations in daylight and better aligns human activities with available light. On the other hand, arguments against the time change point out that energy savings are minimal since modern energy consumption patterns (e.g., the widespread use of heating and cooling systems and electronic devices) mean that any savings in lighting are often offset by increased energy consumption in other areas. Within this context, the studies by Kellogg and Wolff, Kotchen and Grant, and Marshall analyze the effects of DST in different regional contexts (Australia, the USA, and Chile, respectively) and conclude that the introduction or extension of DST does not necessarily lead to energy savings. This conclusion challenges the original premise of DST as an energy efficiency policy. Kellogg and Wolff (Australia), based on “natural experiments” in Australia, found that DST did not result in significant energy savings. Savings in lighting were offset by increased use of HVAC (heating or cooling), especially in extreme climates [6]. Kotchen and Grant (USA) suggest that extending DST may increase energy consumption in certain regions. During the colder months, the increase in heating demand in the dark mornings outweighs the reduction in electricity use for lighting in the evenings [7]. Marshall (Chile) showed that DST had little or no impact on total energy consumption. This may be related to country-specific consumption characteristics and climatic conditions that influence energy use for heating and cooling [8]. The studies highlight the need to reconsider DST as an energy efficiency measure and to explore more effective strategies adapted to regional needs. The study by Shimoda et al. based on energy simulations concludes that the implementation of DST in Osaka, Japan, would lead to an increase in residential electricity consumption, challenging the notion that DST necessarily leads to energy efficiency [9]. The study found that DST not only fails to reduce energy consumption but increases it, mainly due to the increased use of air conditioning during warmer nights and the tendency of residents to extend nighttime activities when the sun sets later. Osaka’s hot and humid climate increases reliance on cooling devices such as fans and air conditioners during the summer months, and prolonged natural light in the late afternoon can increase this demand by creating greater thermal discomfort in the early evening. As the study focused on residential buildings, it was emphasized that these environments are more directly affected by climatic conditions and daily habits than commercial or industrial buildings. However, the increase observed in Osaka reflects a specificity of local climatic conditions and consumption patterns. Similarly, the study by Kandel and Sheridan [10] based on a time series approach analyzed the impact of DST on electricity consumption in California and concluded that the effects are ambiguous because the DST effect on electricity consumption is not uniform throughout the period. In some seasons, energy

consumption may be slightly reduced, while in others it may increase. These variations are attributed to factors such as seasonal climate changes and differences in consumption patterns between sectors (residential, commercial, and industrial). On the other hand, California, with its varied climate (from Mediterranean to desert), has distinct patterns of energy use. On the hottest days, the increase in air conditioning use can outweigh the savings from reducing lighting. The time series approach showed that the effects of DST are difficult to isolate because of the influence of other factors, such as changes in energy prices, improvements in energy efficiency, and variations in demand throughout the year. Kandel and Sheridan's analysis shows that DST in California has an uncertain and variable impact on electricity consumption, calling into question the effectiveness of DST as an energy-saving measure and reinforcing the need for tailored, evidence-based policies at the local level [10].

As regards health effects, they point out that time changes disrupt biological rhythms, leading to sleep disturbances, increased stress, and potential long-term health risks such as heart problems, and link the change to increased rates of accidents and health emergencies, particularly in the week following the change. In terms of economic costs, the disruption caused by the time change can reduce productivity, lead to scheduling inefficiencies, and increase operating costs for businesses, and, in terms of public opinion, surveys in many countries show that a significant proportion of the population would prefer to abolish the time change altogether, opting for either permanent summertime or permanent standard time.

In 2018, the European Parliament voted to end mandatory biannual time changes and allow member states to choose between permanent summer or standard time. However, implementation has been delayed, and most European countries have continued with the time changes [11]. The debate reflects wider concerns, with some advocating permanent summertime to benefit tourism and outdoor activities, while others prefer standard time to better align with natural daylight. Proponents of such a change argue that it would help improve public health, sleep patterns, and productivity. Following the European Parliament's recommendations (2019), most European countries have yet to decide whether they will stick to summer or winter time if the measure is implemented.

The introduction section shows the historical reasons for the introduction of DST and the relevance of the issue in public policy and building management practice. The materials and methods section presents the methodology used to conduct the research and bibliometric analysis, establishing a detailed methodological approach using the Biblioshiny tool version 4.3.0 and conducting a systematic literature review using the PRISMA methodology. The steps of data collection, preparation, analysis, and visualization of the results is described. This section also presents the results of the bibliometric analysis, identifying research trends on DST over the years and illustrating the main themes and contributions. Graphs and tables are presented showing the evolution of the number of publications, influential authors, most frequent keywords, and international collaborations. The most common themes in studies on the subject are also analyzed, such as energy saving, circadian rhythms, and road safety.

The literature review section provides an overview of the existing knowledge on the effects of time changes, with a special focus on energy consumption and energy efficiency of commercial buildings. The contributions of the main studies on DST and its effects on energy consumption, occupant comfort, public safety, and economic impacts are summarized, discussed, and related. Differences in the results of the studies are highlighted, and the complexity of measuring the effects of DST due to regional, climatic, and behavioral factors is emphasized. The conclusions section interprets the results of the bibliometric analysis and literature review and relates them to the objectives of the study. It then ex-

plores the practical implications of the findings, including suggestions for public policy and recommendations for managing buildings in a time change scenario. The limitations of DST as an energy-efficiency policy and possible alternative approaches are highlighted. Finally, the authors highlight the need to develop further studies focusing on regional and cultural specificities.

2. Materials and Methods

2.1. Bibliometric Analysis Procedure

For the bibliometric analysis, the Biblioshiny tool, integrated within the Bibliometrix package in RStudio version 2024.04.2+764, was used. Bibliometrix is a package designed for the analysis and visualization of bibliometric data, particularly useful in literature reviews and scientific trend analyses [12]. The Biblioshiny tool, integrated within the Bibliometrix package in RStudio, was selected for this bibliometric analysis due to its robust capabilities for visualizing and interpreting complex bibliographic data, offering a user-friendly interface compared to alternatives like VOSviewer or CiteSpace. Its ability to generate detailed network maps and statistical outputs aligns with our goal of identifying research trends and thematic connections in DST studies. Similarly, the PRISMA methodology was chosen for the systematic literature review because of its widely accepted framework for ensuring rigor, transparency, and reproducibility, outperforming less structured approaches like narrative reviews by providing clear inclusion/exclusion criteria and a systematic workflow. The methodological steps followed are outlined below:

- Data Collection: The first step involved collecting bibliographic data. For this analysis, a search was conducted in scientific databases using keywords relevant to the study topic. The records were exported in BibTeX format, compatible with Bibliometrix.
- Data Preparation: The BibTeX files were imported into RStudio and directly loaded into the Biblioshiny interface. This step ensured the proper formatting and structuring of the data, allowing for the processing of bibliometric variables such as authors, titles, abstracts, keywords, and institutional affiliations.
- Analysis Setup in Biblioshiny: In Biblioshiny, several relevant bibliometric analyses were configured:
 - Scientific Production Analysis: This involved studying the annual productivity of articles on the topic, identifying publication trends over time.
 - Authors and Institutions Analysis: Identification of the most productive authors and institutions, as well as their collaborations, through co-authorship graphs and collaborative networks.
 - Keywords and Topic Analysis: Analysis of the most frequent keywords and main topics covered in the articles, conducted to understand the thematic focus of the research field.
 - Network Mapping: Creation of network maps, including word co-occurrence networks, co-citation networks, and country collaboration networks, to illustrate the knowledge structure and connections in the studied area.
- Data Analysis and Interpretation: With the analyses configured, Biblioshiny generated graphs and tables for each of the investigated dimensions. The graphical results were used to visualize citation, co-authorship, and keyword patterns, enabling the identification of research trends and gaps.
- Export and Storage of Results: Finally, the results were exported directly from the Biblioshiny interface, in image and table formats, for further analysis and inclusion in the article.

2.2. Literature Review

To conduct the literature review, we based our approach on the results obtained from the bibliometric analysis, using the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). The PRISMA methodology guides systematic reviews in a rigorous manner, ensuring transparency and reproducibility in the criteria for including and excluding studies. The steps followed to conduct this review are outlined below:

- Study Identification: After the bibliometric analysis using Biblioshiny, the main articles, themes, and authors in the field were identified. The bibliometric analysis allowed for visualization of publication trends, frequent keywords, and collaboration networks, resulting in an initial list of potentially relevant articles for the review.
- Creation of the PRISMA Study Flow:
 - Initial Search: The list of articles obtained from the bibliometric analysis was exported and imported into reference management software EndNote 21, where all studies were initially and formally identified for inclusion in the review.
 - Removal of Duplicates: Duplicate records were removed, reducing the set of studies to be analyzed and increasing the efficiency of the selection process.
 - Study Screening: Eligibility criteria were applied based on the titles and abstracts of the articles, considering relevance and alignment with the study objectives. At this stage, articles that did not meet the pre-established inclusion criteria, such as language, scope, and publication period, were excluded.
- Study Selection:
 - Full-Text Evaluation: The articles that passed screening were evaluated in full, following defined inclusion criteria, such as methodological quality, theoretical relevance, and alignment with the focus of the review. This selection process adhered to PRISMA guidelines, with each article independently evaluated by at least two reviewers to reduce bias.
 - Application of Exclusion Criteria: Articles that did not contain relevant data or presented inadequate methodology for the review's purposes were excluded. This stage ensured the inclusion of only high-quality studies directly related to the topic.
- Data Extraction and Analysis:
 - Extraction of Key Data: Relevant information was extracted from the included articles, such as author, year of publication, country, methodology, main findings, and conclusions. The extracted data were organized in a table to allow for a comparative view across studies.
 - Thematic Analysis: Based on the keywords and recurring themes identified in the bibliometric analysis, main themes were defined to guide the discussion. This thematic analysis facilitated the identification of patterns, significant contributions, and knowledge gaps in the field.
- Synthesis and Discussion: Finally, the results of the analysis were synthesized, emphasizing the main contributions, trends, and gaps identified in the literature, according to the bibliometric results. The PRISMA methodology contributed to a structured and rigorous presentation of the review, providing a clear view of existing approaches and potential areas for future research.

3. Bibliometric Analysis Results

3.1. Bibliometric Analysis of the Data

As can be seen in Table 1, the bibliometric analysis covers the period from 1968 to 2023, including 139 documents from 109 sources, encompassing scientific journals, books, and other types of publications. These results reflect a field of study with a moderate annual growth rate of 2.02%, indicating a steady, though modest, increase in interest over the years. The average age of the documents is 13.1 years, suggesting a well-established literature base while also indicating the presence of recent publications. The average number of citations per document is 15, demonstrating considerable impact within the scientific community. The 3638 cited documents reinforce the depth and richness of the literature associated with this field of study.

Table 1. Main information about data.

Description	Results
Timespan	1968:2023
Sources (journals, books, etc.)	109
Documents	139
Annual growth rate %	2.02
Document average age	13.1
Average citations per doc	15
References	3638
Document contents	
Keywords Plus (ID)	1066
Author's Keywords (DE)	293
Authors	
Authors	360
Authors of single-authored docs	35
Authors collaboration	
Single-authored docs	38
Co-authors per doc	2.76
International co-authorships %	16.55
Document type	
Article	100
Conference paper	31
Conference review	1
Erratum	1
Note	1
Review	4
Short survey	1

In terms of document content, 1066 additional keywords (Keywords Plus) were identified from the titles of referenced articles, along with 293 keywords provided directly by the authors. This disparity highlights the breadth of topics associated with the field, reflecting a diversity of subjects explored beyond those specifically chosen by the authors.

The author analysis reveals a total of 360 researchers involved, of whom 35 contributed single-authored publications. The relatively low number of single-authored documents (38 in total) reinforces the collaborative nature of this field of study. The average number of co-authors per document is 2.76, with international collaboration present in 16.55% of cases, indicating openness to global cooperation, though with room for expansion.

Regarding document types, most publications consist of journal articles (100), followed by conference papers (31), reflecting an interest in disseminating both complete studies and preliminary results at scientific events. Other types of documents, such as reviews, notes, and errata, are present in smaller quantities, adding diversity but remaining less representative.

3.2. Analysis of Frequent Terms in DST Research

The analysis of term frequency highlights the main themes and subtopics addressed in DST research, providing insights into the focus and diversity of studies in this area. The most frequent term is “daylight saving time” (57 occurrences), which reflects the central topic of the research. Following this, “energy conservation” (43 occurrences) indicates that a significant portion of studies is focused on DST’s potential to reduce energy use, emphasizing the economic and environmental aspects of time changes. Figure 1 shows the results in a word cloud.



Figure 1. Word cloud.

DST research also strongly focuses on impacts on human health, as evidenced by terms such as “circadian rhythm” (29), “human” (25), “humans” (21), and “sleep” (14). These terms indicate a significant interest in exploring how DST affects biological rhythms, sleep, and overall well-being. The presence of terms like “female” (14) and “male” (12) further suggests that some studies consider gender differences in DST’s impact, broadening the understanding of varied responses to time changes.

The term “United States” (19 occurrences), followed by “Australia” (10), suggests that DST research is particularly concentrated in these countries. This geographical focus may reflect the prominence of studies conducted in these regions or a specific interest in DST policies there. The prominence of the United States and Australia may be related to the historical context or the availability of longitudinal data that facilitate deeper analyses.

Traffic safety is a recurring theme in DST research, with terms such as “traffic accident” (16), “accidents” (12), “traffic” (11), and “highway accidents” (7) appearing frequently. These terms indicate that DST may be associated with accident rates, possibly due to changes in sleep patterns and daylight exposure during peak commuting hours. The connection between DST and traffic safety highlights the potential social impact of time changes and underscores the relevance of informed public policy.

Several terms related to energy use, such as “electric power utilization” (13), “energy use” (12), “energy policy” (11), “energy efficiency” (10), and “electricity-consumption” (9), reflect an interest in investigating DST’s impact on energy demand and efficiency.

These terms suggest that research extensively explores DST within the context of energy management policies, evaluating its role in energy savings and optimizing resource use.

Terms such as “season” (11), “seasons” (11), “sunlight” (9), and “seasonal variation” (6) indicate that research also considers the effects of seasonal changes and daylight exposure. This focus suggests that DST is studied to optimize natural light usage and reduce the need for artificial lighting, with potential implications for energy conservation and environmental impact.

The presence of terms like “regression analysis” (8), “mathematical models” (7), and “controlled study” (6) suggests that DST studies frequently employ rigorous quantitative methods and controlled empirical approaches. These terms indicate an emphasis on statistical analysis and mathematical modeling to evaluate DST’s effects precisely and reliably, ensuring robust results.

The analysis of frequent terms reveals that DST research is broad and interdisciplinary, addressing complex interconnections among energy policy, human behavior, public health, and environmental factors. The strong focus on energy conservation, human health (particularly circadian rhythms and sleep), and traffic safety shows that DST is a topic with significant social and economic implications. The geographical emphasis on the United States and Australia suggests that these countries play a central role in producing knowledge about DST, possibly influencing policy formulation in these regions.

These bibliometric findings underscore the relevance of energy conservation and human health as dominant themes in DST research, both of which directly pertain to the energy efficiency and occupant comfort in commercial buildings. The frequent occurrence of terms like “energy efficiency” and “electricity consumption” suggests a strong research focus on optimizing energy use, a critical concern for commercial buildings where lighting and HVAC systems dominate consumption profiles. Similarly, the emphasis on “circadian rhythm” and “sleep” highlights occupant well-being, which influences productivity and thermal comfort perceptions in office settings. This thematic convergence supports our study’s objective to assess how DST impacts commercial buildings, indicating that energy savings and occupant-related factors are intertwined challenges requiring integrated management strategies.

3.3. Evolution of Citations over the Years

Table 2 reveals interesting patterns in the evolution of citations over time, highlighting periods of higher impact and recent growth in interest in the field. The Mean Total Citations per Article (MeanTCperArt) column, representing the average citations per article for each year, suggests that certain years were particularly influential. Notably, publications from 2002, 2008, and 2011 show high average citation counts per article, with 78, 41.25, and 88.75 citations, respectively. These peaks indicate that research published in these years was highly relevant to the field and continues to be widely referenced.

Another point of interest is the Mean Citations per Year (MeanTCperYear), which reflects the average annual citations for articles from each publication year. High values for 2011 (6.83), 2002 (3.55), and 2016 (3.25) indicate that articles from these years continue to be relevant and frequently cited, suggesting a sustained impact over time. The continuity of citations for these articles indicates that they address fundamental issues or present innovative findings, maintaining their relevance within the field of study.

Table 2. Evolution of citations over the years.

Year	MeanTCperArt	N	MeanTCperYear	CitableYears
1968	16	1	0.29	56
1976	32.5	2	0.68	48
1977	0	1	0	47
1978	14	1	0.3	46
1979	14	1	0.31	45
1980	0	1	0	44
1981	0	1	0	43
1984	0	1	0	40
1987	0	1	0	37
1989	6.25	4	0.18	35
1990	3	2	0.09	34
1993	6	1	0.19	31
1994	0	1	0	30
1995	0	1	0	29
1996	1.5	2	0.05	28
1997	10.67	3	0.4	27
1999	4	1	0.16	25
2000	11.67	3	0.49	24
2002	78	2	3.55	22
2003	2	1	0.1	21
2004	26.5	2	1.32	20
2005	0	2	0	19
2006	8	1	0.44	18
2007	16.6	5	0.98	17
2008	41.25	4	2.58	16
2009	12.5	2	0.83	15
2010	17.5	8	1.25	14
2011	88.75	8	6.83	13
2012	11.33	6	0.94	12
2013	12	2	1.09	11
2014	10.25	4	1.02	10
2015	3	1	0.33	9
2016	26	4	3.25	8
2017	11	5	1.57	7
2018	7.33	9	1.22	6
2019	3.9	10	0.78	5
2020	9.45	11	2.36	4
2021	1.29	14	0.43	3
2022	0.14	7	0.07	2
2023	0	3	0	1

Regarding the Number of Articles (N) published annually, there is a gradual increase in the volume of publications starting from 2018, reaching a peak in 2020 with 11 articles. This rise suggests growing research interest in the area, possibly driven by new developments or the need to address emerging issues. However, the average citation count for more recent articles is lower, which is expected due to the short time since their publication and, therefore, the limited time available for citation accumulation.

The Citable Years column shows the number of years each publication has been available for citation. This factor is particularly important for understanding the impact of older publications, such as those from 1968 (56 years of citation) and 1976 (48 years of citation), which have had a long period to accumulate citations. In contrast, more recent publications have not yet had sufficient time to reach their full citation potential, explaining the lower average citation counts for the years from 2021 onward.

The data suggest that 2002, 2008, and 2011 were periods of high-impact scientific production, with publications that significantly influenced the research area. This pattern indicates the possible presence of foundational studies or new insights that gained wide acceptance and were frequently cited. The recent increase in the number of publications, especially from 2018 onward, reflects growing interest and activity in the research area. However, the low average citation count for recent years is likely due to the limited time for citation accumulation as these publications are still in the early stages of recognition.

3.4. Geographical Distribution of Research Output

The analysis of Figure 2 reveals a notable concentration of research contributions by country, with the United States (84 publications) being the leading contributor, significantly ahead of other countries. This dominance suggests that research in this field is heavily driven by institutions and scholars based in the US, likely reflecting both the country's research funding capacity and the prominence of its academic institutions.

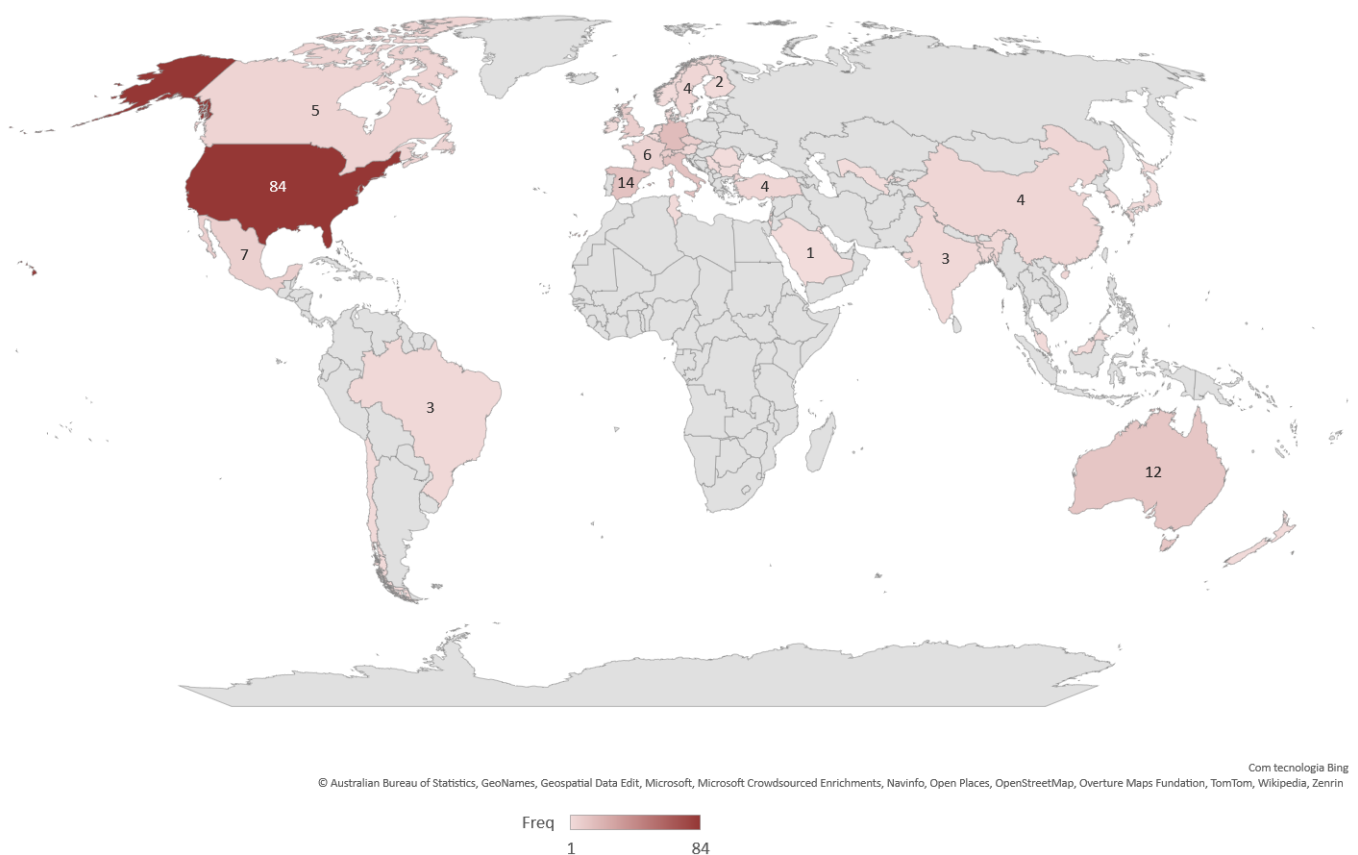


Figure 2. Geographical distribution of research output.

Germany (17 publications), Italy (14), Spain (14), and Australia (12) follow the US, indicating a strong European presence in the field, with notable contributions also from Australia. The Czech Republic, Switzerland, and the United Kingdom each have eight publications, showing substantial involvement from both western and Central Europe.

A moderate number of contributions come from Mexico (7), France (6), and Canada (5), indicating some research activity in North America beyond the US and in key European and Latin American countries. Other countries such as China, Israel, the Netherlands, Sweden, and Turkey each have four publications, reflecting a more globally dispersed interest but still at lower levels of engagement compared to the top contributing nations.

Countries with smaller frequencies, including Brazil, Austria, India, Bangladesh, and others, indicate occasional contributions, which may be driven by specific research groups

or individuals rather than a sustained national effort. Countries with a single publication, like Belgium, Japan, and Singapore, reflect minimal but present engagement in the field.

This geographical distribution highlights that the research field is predominantly concentrated in a few leading countries, primarily in North America, Europe, and Australia, with less frequent contributions from Latin America, Asia, and the Middle East. The data also reveal limited participation from African nations, which could suggest a potential area for increased research activity and collaboration in the future.

3.5. Relationships Among Sources, Authors, and Keywords

Figure 3 presents a visualization of bibliometric connections through a Sankey diagram, illustrating the relationships among sources (SO), authors (AU) and keywords (DE) associated with the studies analyzed. This structure provides a clear view of the influence flows among key studies, authors, and sources in the field of daylight saving time (DST) and its impacts.

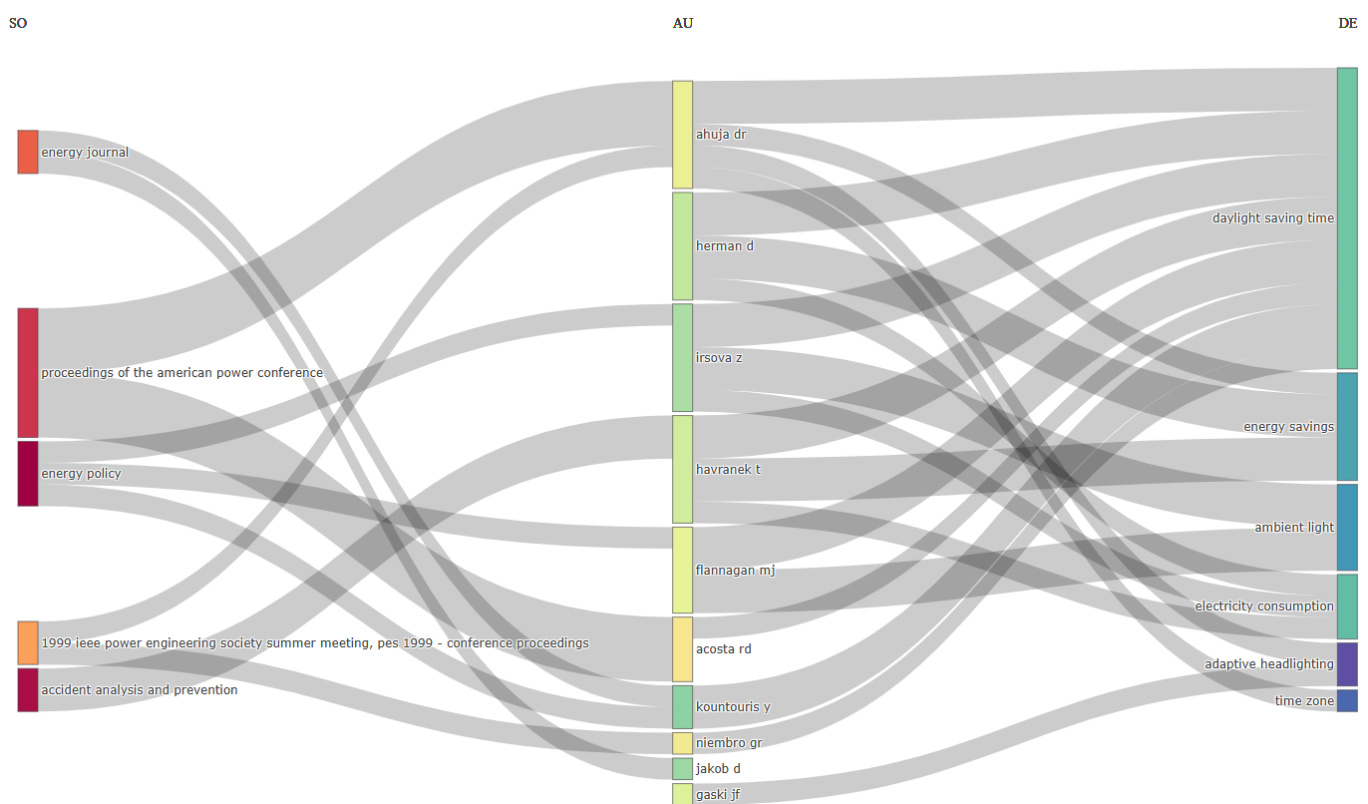


Figure 3. Relationships among sources, authors, and keywords.

On the left side, we find the original sources, indicating studies that play a fundamental role in the research field. These sources cover topics such as energy policies, energy journals, proceedings of the american power conferences, accident analysis and prevention and other conference proceedings.

In the central column, authors serve as a crucial link between sources and keywords. The connection between authors and sources suggests a collaborative and interdisciplinary research network, where authors share and build upon each other's work to deepen the understanding of DST's impacts. Furthermore, the number of connections certain authors have with specific sources and keywords indicates that they play a central role in specific topics, significantly contributing to the advancement of areas such as energy savings, circadian rhythms, and safety.

The right column includes keywords, reflecting the main themes addressed in the literature. Topics such as “daylight saving time”, “energy savings”, “electricity consumption”, and “circadian rhythms” appear frequently, showing that the field focuses heavily on understanding the effects of DST across different domains. The dense connection between certain keywords and specific authors indicates a consolidated thematic structure, where several investigations explore similar issues. This pattern suggests that the field of study, while diverse, has well-established and recognized core themes.

The lines between columns represent connections among, sources, authors and keywords, revealing influence flows within the field. These connections indicate how specific authors and topics are interconnected. For instance, the strong presence of lines between classic references on DST’s impact on health and energy and authors specializing in these areas suggests that these topics are fundamental to current research. The complexity of the network also highlights the interdisciplinary nature of the field, integrating approaches from areas such as economics, environmental science, public health, and human behavior.

This visual analysis demonstrates that the DST research field is built around a solid foundation of widely studies and well-defined core themes. The strong connections observed among related keywords, such as “daylight saving time” and “energy savings”, show thematic cohesion, suggesting that, while the field encompasses various subtopics, there is significant convergence around main themes. The presence of topics like public health and electricity consumption also underscores the social and economic relevance of the research, indicating that DST effects are complex and multifaceted, with implications beyond mere energy savings.

The analysis of collaborations and sources indicates that the field is internationally relevant, although there remains a predominance of specific countries, as previously shown in the geographical analysis.

3.6. Co-Occurrence Analysis of Keywords

Figure 4 presents a network of keyword co-occurrences, highlighting the main themes and subthemes of research on daylight saving time (DST). The keywords are organized into clusters, differentiated by colors, indicating associated thematic areas and their interconnections. The visual structure shows the frequency and proximity of keywords, suggesting which topics are frequently explored together and which have a stronger thematic relationship.

On the right side of the figure, a red cluster focuses on keywords related to energy conservation and energy policy. This group includes terms like “electric power utilization”, “energy efficiency”, “electricity consumption”, and “energy policy”, all closely connected to “daylight saving time”. The presence of terms such as “demand analysis” and “electricity supply” within this cluster suggests that a significant portion of research focuses on the effects of DST on electricity consumption and energy efficiency, with implications for energy management and policy formulation. This focus on energy conservation reflects concerns about the rational use of energy resources and DST’s potential role as a strategy to reduce electricity demand.

On the left side of the figure, the blue cluster groups keywords centered on DST’s impacts on human health and circadian rhythms. Terms like “circadian rhythm”, “traffic accident”, “sleep”, and “wakefulness” highlight the research interest in understanding how time changes affect human well-being. Keywords such as “human”, “accidents”, and “sleep” point to studies exploring the effects of DST on biological rhythms, sleep quality, and road safety. The presence of terms like “walking/highway accidents” suggests that DST may be linked to an increase in accidents, possibly due to changes in sleep cycles and adaptation to the new time.

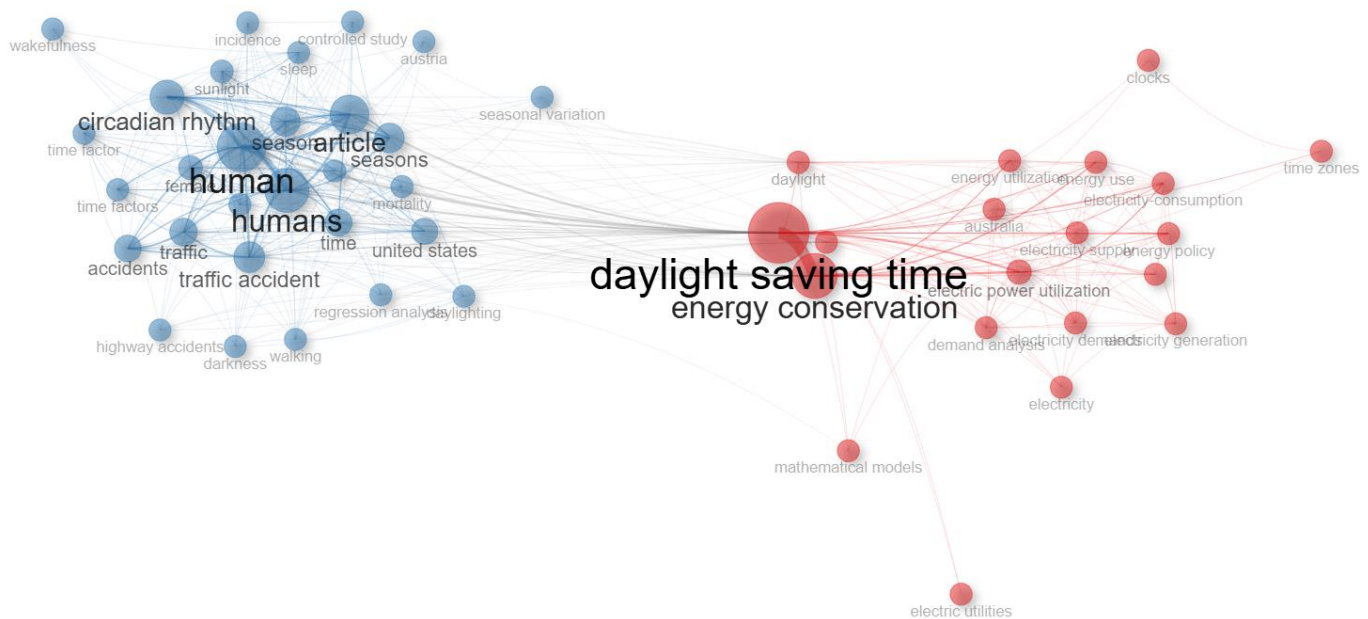


Figure 4. Co-occurrence analysis of keywords.

The keyword “daylight saving time” occupies a central position in the network, serving as the intersection between the red and blue clusters. This central position indicates that DST is the common theme connecting discussions on energy conservation and human health. The centrality of “daylight saving time” reflects its role as a unifying concept that links economic and energy effects to physiological and social impacts.

The connections between clusters suggest an interdisciplinary approach to investigating DST impacts, involving both exact sciences and health sciences. The proximity of energy- and health-related themes in the network suggests that studies often address DST in a holistic manner, considering both its potential benefits for energy conservation and its consequences for human well-being.

4. Results and Discussion

4.1. DST Brief Historic Analysis

The concept of daylight saving time (DST) originated in the idea of changing clocks to make the most of natural daylight at certain times of the year. Ancient societies, such as the Romans, employed water clocks that changed time according to the seasons and had separate time scales for day and night. Benjamin Franklin (1784), in a satirical essay, suggested that getting up earlier in the summer could save on lighting candles. This idea was more about changing personal behavior than formally changing clocks [13]. New Zealand entomologist George Vernon Hudson (1895) suggested a two-hour time change to provide him more daylight for his nighttime research, and British builder William Willett pushed for DST in 1907 so that people may enjoy more daylight for outdoor activities [14,15].

During the First World War (1916), Germany and Austria–Hungary were the first countries to introduce summertime, on 30 April 1916, to save coal during the war. Other countries such as the United Kingdom, France, and the United States followed shortly afterwards. During the inter-war period, DST was repeatedly abolished and reintroduced in different countries because of conflicting public opinion. The economic benefits were often outweighed by confusion and opposition from farmers and rural communities. During the Second World War (1939–1945), DST was reintroduced as an energy-saving strategy. “Wartime” was introduced by the USA, which meant that clocks ran on DST all year round. After the war, the United States gave states and localities the freedom to decide whether to

observe daylight saving time, which caused scheduling chaos. States could choose not to use DST, but the Uniform Time Act of 1966 standardized the start and end dates nationwide. Later, interest in DST as an energy-saving strategy was revived by the 1973 oil embargo. Similar measures were taken around the world after the United States extended DST in 1974–1975. The European Union standardized DST among its member states in 1996, while the Energy Policy Act of 2005 allowed the United States to extend DST by a few weeks in 2007. The EU agreed in the 2019 European Union Decision to end seasonal clock changes by 2021, allowing each nation to set its own permanent time. However, implementation has been delayed.

The shift from DST to standard time occurs in each country according to individually defined rules. Nevertheless, some countries have never adopted DST due to the minimal variation in daylight hours throughout the year, particularly those near the equator, notably the following: Saudi Arabia, which is close to the equator and has relatively consistent sunrise and sunset times throughout the year; Venezuela, with its tropical location, sees little benefit from adjusting clocks; and Afghanistan, given its focus on agriculture and traditional timekeeping [16]. On the other hand, several countries used to observe daylight saving time but have abandoned the practice for reasons related to public inconvenience, questionable energy savings, or alignment with neighboring countries. Some examples include Russia, which abandoned DST in 2011 and moved to permanent “summertime” before moving to permanent “standard time”. The decision was influenced by concerns about health effects and confusion caused by frequent clock changes; Brazil, which stopped DST in 2019, citing that modern energy consumption patterns (e.g., the widespread use of air conditioning) made DST ineffective in saving energy; and Peru, which abandoned DST due to limited energy savings and lack of public support. In fact, of the 195 recognized countries, only 82 still observe DST changes, mainly in North America, Europe, and parts of the Middle East and Oceania [17]. As referred to, in the European Union, it was agreed that time changes would occur simultaneously, even in different time zones. However, in other parts of the world, this shift does not happen at the same time. For example, Chile adjusts its clocks a week before Paraguay, despite their geographic proximity. Due to the Sun’s movement between the northern and southern tropics, the seasons also change depending on a location’s position on the globe. In December, the Sun is closer to the Earth in the Southern Hemisphere than in the Northern Hemisphere. Thus, during the winter months in the Northern Hemisphere, it is summer in countries south of the equator. Consequently, people in the Southern Hemisphere switch to DST, while those in the Northern Hemisphere move to standard time. Figure 5 illustrates global time zones, showing longitudinal variations and how different countries adopt daylight saving time in a non-uniform manner. Regarding longitude, we can observe that different time zones exist along the same longitude. Within a single country, there may be areas observing DST and others in a different time zone.

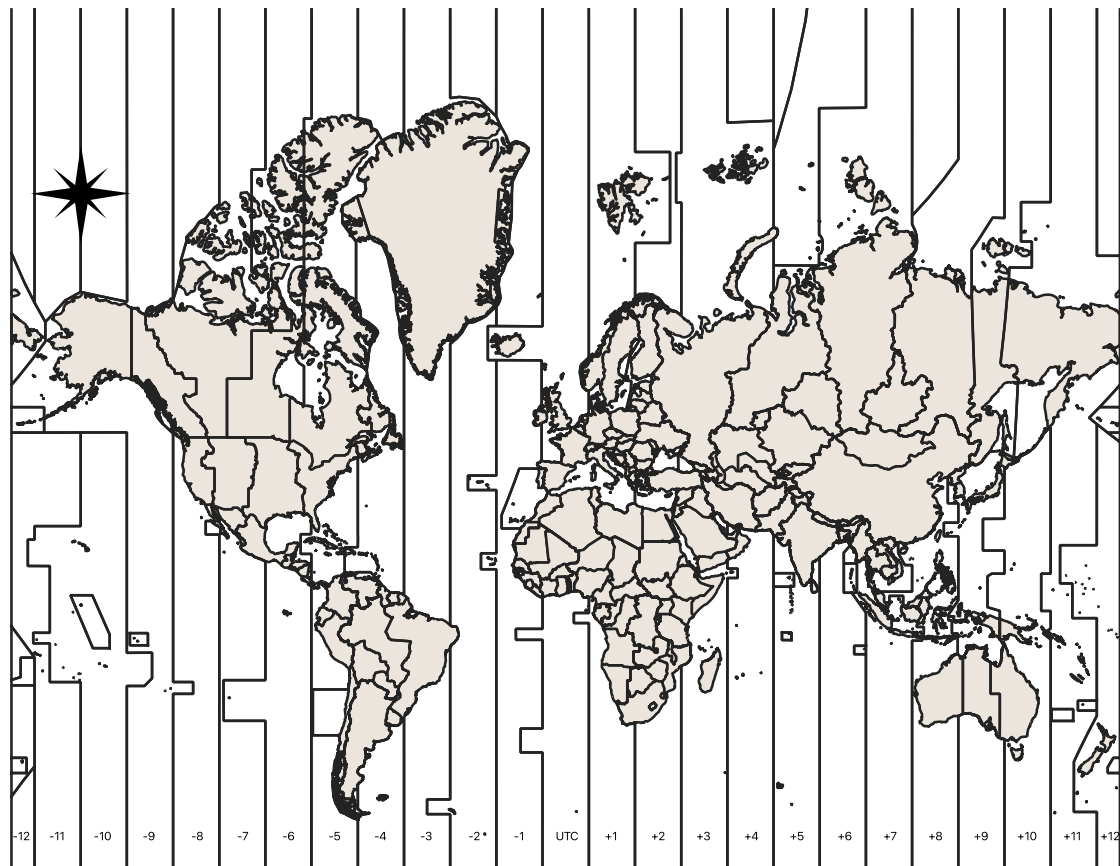


Figure 5. Map of time zones.

4.2. DST Without the Energy Component

Several studies suggest that time change can affect people's health and well-being [18]. The abrupt change in circadian rhythms can lead to sleep disturbances, fatigue, irritability, and even more serious health problems such as heart attacks and strokes [19]. Other studies show an increase in sexually transmitted diseases and road accidents [20]. On the other hand, proponents of summertime time argue that the increased amount of sunlight can improve people's mood and physical activity [21]. It is also known that some people enjoy the longer days of summertime, while others report discomfort from the disruption to their daily rhythms [22].

Regarding the economic impact of the time change, some studies suggest savings in sectors such as retail and tourism due to the longer hours of daylight at night, while others point to costs associated with adapting technology systems and reduced productivity after the change [23]. Productivity is also controversial, with some studies suggesting a short adjustment period that may lead to a temporary drop in productivity, while others find no significant correlations [24].

Sleep deprivation among workers is one of the main justifications proposed in the literature to explain productivity losses around summertime changes. For example, Gibson and Shrader's (2018) [24] study examines the impact of natural light, as determined by sunset times, on human behavior and outcomes such as sleep and income. By analyzing variations in sunset times across time zones, they show how natural light affects people's daily routines and economic productivity. The study shows that disrupted sleep patterns due to variations in sunset times can have wider economic implications. These findings suggest that policies or practices that align work schedules with natural light patterns could improve sleep health and economic outcomes. It also highlights the indirect costs of sleep

deprivation caused by environmental factors such as sunset timing, which is relevant to discussions of DST policies [11]. Similarly, a study by Giuntella and Mazzonna (2019) [25] examines the relationship between natural light exposure, circadian rhythms, and socio-economic outcomes, with a particular focus on health and per capita income. Their findings highlight the important role that natural light, which regulates our internal biological clock, plays in influencing health and economic productivity, illustrating the interrelated effects of natural light on individual and societal well-being [12]. Likewise, the study by Costa-Font et al. (2024) [26] examines the relationship between sleep patterns and economic outcomes, particularly employment and income, and provides further evidence of the significant role of sleep in labor market productivity and financial well-being, emphasizing that sleep is not just a health issue but a cornerstone of economic productivity and stability. It is consistent with growing evidence that policies to promote better sleep hygiene could lead to improved socio-economic outcomes [26]. In a similar vein, the study by Barnes and Wagner (2009) [27] provides critical insights into the effects of DST on sleep and activity at work, with a particular focus on US coal miners. Their research highlights how the transition to summertime disrupts sleep patterns and contributes to changes in work performance, illustrating how DST transitions can have unintended consequences in industries where sleep and physical performance are closely linked. They make a compelling case for reconsidering the role of DST, particularly for labor-intensive sectors [27].

Dickson and Waddell (2024) [28] investigated the impact of DST on productivity in global technology centers by examining variations in its implementation. Their findings suggest that the net productivity effect of DST in technology centers depends on the interplay between improved work–life dynamics and coordination challenges in a globalized industry. The study highlights the importance of considering industry-specific factors when assessing the broader economic impact of DST by analyzing GitHub activity in cities that observe DST; their findings highlight notable productivity patterns around the DST transition [28]. The authors refer that there was a marked decrease in GitHub activity on the Sunday of the DST transition and the following Monday. While daily activity generally returned to baseline levels after these two days, the Sunday effect persisted in the form of reduced activity on subsequent Sundays in treated cities. An hourly analysis revealed that the transition caused extended disruptions to morning productivity. These declines were observable for over two weeks after the start of DST, suggesting a prolonged adjustment period for individuals adapting to the time shift. These findings challenge the notion that DST's impact on productivity is short-lived. While overall daily activity may normalize quickly, specific patterns, such as diminished Sunday output and persistent morning disruptions, indicate a more complex and enduring cost to productivity associated with DST transitions. Similarly, Kountouris and Remoundou (2014) [29] explored the impact of the DST transition on individual well-being, focusing on data from Germany. Their analysis found that the DST transition was associated with a measurable decrease in overall life satisfaction; participants reported a decrease in positive mood following the DST transition, highlighting the psychological distress caused by the change in schedule, and the negative effects were more pronounced among those in full-time employment, likely due to the rigid structure of work schedules that makes it more difficult to adapt to the time shift. These findings underline the wider societal costs of daylight saving time transitions, suggesting that the disruption of natural circadian rhythms has tangible consequences for both mental health and workplace productivity, particularly for those with fixed daily routines [29].

Other studies report that, despite the energy concerns, the effects of introducing DST can affect various aspects of society, which are often difficult to quantify and may vary by region and population. In terms of road safety, longer daylight hours during the evening commute may improve visibility and reduce accidents. In this regard, Ferguson et al.

(1995) found that shifting clock times so that peak traffic periods occur during daylight hours can lead to a reduction in overall road accidents [30]. By aligning peak traffic periods with natural light, visibility is improved and, therefore, safety. On the other hand, the study reports that the sudden change in clock time disrupts sleep patterns and that this sleep disruption may temporarily increase the risk of accidents immediately after the change. This means that while DST may offer long-term safety benefits by reducing evening accidents, the short-term effects around the time of the change could lead to an increase in accidents. Similarly, a study by Doleac and Sanders (2015) found that extending daylight hours into the evening significantly reduced robbery rates [31]. This finding highlights one of the potential social benefits of DST beyond its original energy-saving purpose, although its magnitude and persistence may vary by region and local context.

In terms of economic activity, Kamstra et al. (2000) showed that the clock change can disrupt the financial system [32], and Müller et al. (2009) highlighted the sensitivity of the results to the methods and data used, emphasizing that DST can extend usable leisure time in the evening by providing additional natural light, which in turn can encourage outdoor activities, improve physical health, and promote social interactions that vary by demographic group and region [33].

In contrast, studies by Lahti et al. (2010) and Toro et al. (2015) show that the abrupt clock change can lead to significant sleep deprivation and physiological stress, which in turn reduces productivity and overall well-being due to the misalignment between the biological clock and social time [34,35]. Both studies highlight the trade-offs involved in DST policies, where gains in evening light for leisure or safety may be offset by adverse health effects in the days immediately following the time change.

Likewise, research by Shapiro et al. (1990), Olders (2003), and Kuehnle and Wunder (2016) [36–38] suggests that the abrupt changes in daylight exposure and sleep cycles associated with DST transitions may exacerbate conditions such as seasonal affective disorder (SAD) and overall mood. In short, while DST may offer benefits in terms of extended evening light, its impact on psychological well-being needs to be considered [36–38].

Therefore, while DST is often discussed in terms of electricity savings, its long-term effects on road safety, crime rates, economic activity, leisure, and health are equally important and deserve careful consideration of their societal impact.

4.3. Potential Energy Savings with DST

4.3.1. The Overall Impact of DST on Energy Efficiency

Prerau David S. (1977) [39] pointed out that summertime was introduced mainly to save energy during the Second World War by making use of natural light, suggesting that the extra hour of daylight in the late afternoon reduces the need for artificial lighting and, therefore, saves electricity. However, these savings may be partially or fully cancelled out by increased lighting in the early morning when the sun rises earlier. In other terms, the net energy benefit of summertime tends to be greater when the sun rises earlier and less when it rises later. According to Prerau, the overall effect of DST is to save about 1% of electricity in spring and autumn by reducing evening lighting demand, but the net effect is highly sensitive to the local timing of sunrise and sunset [39].

Continuing with the study of the impact of DST on energy efficiency, Rock (1997) [40], examined the impact of DST on energy use and costs in residential buildings by using the DOE-2.1 E simulation code to evaluate the effects of implementing DST on HVAC systems and lighting energy use. A case study of a typical U.S. residential building in Lawrence, Kansas, served as the baseline model, and simulations were conducted for 224 different locations across the U.S. Data for the simulations were derived from the home's operating hours and electricity and natural gas bills.

The results show that using DST during winter standard time slightly increased total annual energy costs by an average of 0.147% compared to maintaining year-round standard time and that switching from year-round standard time to DST did not result in significant changes in energy use or costs for the homes studied. However, replacing winter standard time with summertime led to a slight reduction in average energy consumption and costs. Taking this into account, the study suggests that the impact of summertime on energy efficiency may not be significant for typical residential buildings [40].

On this basis, Myriam B.C. Aries et al. (2008) [41] conducted one of the first comprehensive literature reviews, entitled *Effect of Daylight Saving Time*, which highlighted the limitations and inconsistencies of existing research on the impact of DST on energy consumption. Their study highlighted several challenges and complexities that make understanding the effects of DST particularly difficult, mainly by highlighting knowledge gaps in existing studies, which were often limited, incomplete, or contradictory, making it difficult to draw definitive conclusions about the energy-saving effects of DST. The inconsistencies are attributed to the age of the studies, which may not have considered technological advances and changes in energy consumption patterns. On the other hand, there were significant differences in the criteria and definitions of the studies reviewed, which led to differences in methodology and results. In short, the authors highlight the need for more rigorous and updated research to understand the true impact of summertime on energy consumption. Future studies should adopt standardized methodologies and consider a wide range of factors, including regional contexts, technological advances, and evolving human behavior. Without these improvements, conclusions about the effectiveness of DST in saving energy will remain uncertain and controversial [41].

More recently, Havranek et al. (2018) [42] conducted a comprehensive meta-analysis to explore the energy savings associated with DST. Their study synthesized the results of 162 estimates from 44 studies, providing a nuanced understanding of the impact of DST on electricity consumption. The analysis found an average electricity saving of 0.34% due to DST, but this estimate was overstated due to the quality of the data used, the methodologies applied in the studies, and publication biases, such as the tendency to report positive results. The authors find that when studies with rigorous methodologies (e.g., high-frequency data and difference-in-differences approach) and publications in prestigious journals were given more weight, the average energy-saving effect approached zero. The study finds that the effectiveness of DST in saving electricity varies significantly between countries; this is due to factors related to latitude and proximity to the equator (countries further from the equator achieve greater energy savings) and to the duration of DST as countries with longer DST periods tend to achieve greater savings because the cumulative effect of the shift in daylight hours is more pronounced. In short, the Havranek et al. (2018) [42] study provides robust evidence that the overall energy savings from DST are minimal, if not negligible, when rigorous methodologies are applied. While DST may deliver modest savings to certain regions (e.g., higher latitudes), its benefits are increasingly questionable, especially in light of global advances in energy efficiency and changing consumption patterns [42].

4.3.2. Regional Studies on the Impact of DST on Energy Demand

In the UK, Littlefair's (1990) [43] study examined the relationship between clock settings and daylight hours and proposed and evaluated the effects of three clock setting options: Daylight Saving Time (DST), which applies from March to October and represents the standard seasonal adjustment of clocks; Summer Time, which applies from March to September and is similar to DST but ends one month earlier; and Seasonal Daylight Saving Time (SDST), which corresponds to DST with an additional hour of adjustment (double DST) from March to September. Littlefair recommended SDST over the other

options because it provides a closer match between daylight availability and working hours, optimizing the use of natural light. Switching from standard DST to SDST could reduce total household lighting consumption by just over 5%. Littlefair's research laid the groundwork for subsequent analyses of daylight saving policies, demonstrating that adjustments such as SDST can have a significant impact on energy consumption [43].

Also in the UK, Hill et al. (2010) [44] provided an insightful analysis of the potential energy and environmental benefits of year-round DST, concluding that maintaining DST in winter could save at least 0.3% of daily energy demand. The study estimated a reduction in energy costs of around 0.6% over the months analyzed, contributing to economic benefits for both consumers and energy suppliers. Similarly, maintaining time could save around 450,000 tones of CO₂ emissions, contributing to the UK's environmental targets. The authors stress that moving the clocks forward one hour in winter not only aligns energy use with daylight hours but also has positive implications for sustainability and cost-effectiveness. The findings are consistent with previous research and strengthen the case for year-round DST as an effective energy management and environmental protection measure. The study by Hill et al. highlights the tangible benefits of year-round DST in the UK, including energy savings, reduced costs, and lower carbon emissions. This evidence supports the consideration of DST adjustments as part of wider energy efficiency and environmental strategies [44]. The findings of Hill et al. (2010) [44] on the benefits of maintaining DST throughout the year are consistent with previous research in the literature.

Kudela et al. (2020) [45] provides a detailed analysis of the impact of DST on electricity consumption in Slovakia. Using hourly electricity load data from 2010 to 2017 and considering factors such as weather conditions, macroeconomic variables, the annual cycle, and seasonal variations in the data analysis, the study shows that the introduction of DST leads to an estimated reduction in annual electricity consumption of around 1%. However, using results extrapolated from a previous cross-country meta-analysis, the savings for Slovakia are estimated to be lower, not exceeding 0.5%. The introduction of DST appears to smooth the electricity demand curve, potentially reducing peak loads and improving grid stability. The results reinforce the need for country-specific analyses of DST as its effectiveness varies according to geographical, economic, and cultural factors and underlines the importance of balancing energy savings with other social and economic considerations [45].

Marija Grujić et al. (2018) [46] studied how DST affects energy use in office buildings in a mid-latitude European climate for the city of Belgrade, Serbia. They concluded that in Belgrade's moderate continental climate, where the warm season lasts for six months and cooling is only required for three months, the annual energy use in office buildings is largely dominated by heating. However, during the DST period (April–October), the energy demand shifts: instead of being dominated by heating, office buildings face increased consumption for lighting and air conditioning. By moving the clock forward, DST alters key local climatic parameters such as temperature, daylight availability, and solar radiation, thereby changing the potential for using natural light and reducing artificial lighting loads. However, because DST was originally designed to target lighting savings, its benefits become less pronounced when modern energy consumption patterns, such as heavy cooling use, prevail. In short, while DST can help save energy in buildings where lighting is the main concern, its effectiveness in a context like Belgrade depends on the fine tuning between reduced lighting needs and increased cooling needs [46].

Lopez (2020) [47] studied the impact of DST policies on energy consumption in inland Spain, considering the widespread adoption of LED lighting, which reduces the overall share of lighting in energy consumption. According to the authors, LED lighting has reduced the energy-saving impact of DST on total consumption, although daylight hours still have a significant impact on grid load, up to 5% near sunrise and 15% near sunset. For

the analysis, the authors simulated three scenarios: year-round wintertime (UTC+1), year-round summertime (UTC+2), and current DST with a 1-hour backward adjustment (GMT). The study highlights the importance of context-specific, data-driven analysis in the design of DST policies. For inland Spain, year-round summertime (UTC+2) appears to deliver the best energy savings and load-smoothing results. At the same time, other scenarios (especially GMT) may lead to higher consumption and peak demand challenges [47].

In the US, Sven Eggimann et al. (2023) [48] noted that although DST was originally introduced to reduce the need for artificial lighting, its impact on building heating and cooling loads is dramatic. A series of office buildings in 15 US cities were subjected to energy simulations under current climate conditions, which showed that DST can result in cooling energy savings of up to 5.9% during peak cooling periods while at the same time increasing heating demand by about 4.4% during the same period. According to the authors, while DST still reduces lighting demand, its net impact on total energy use depends on the balance between reduced cooling loads and increased heating loads. These findings highlight that the energy-saving benefits of DST are now closely linked to how buildings manage thermal comfort, suggesting that policy decisions should consider not only lighting but also the changing dynamics of heating and cooling energy demand [48].

Verdejo et al. (2016) [2] analyzed the impact of DST on residential electricity consumption in Chile, providing evidence of significant energy savings attributable to the policy. The study found that the application of DST led to an average reduction in residential electricity consumption of 3.18%. During the morning peak hours (5–10 a.m.), consumption fell by 4.4%, and, during the evening peak hours (5–11 p.m.), the reduction was even greater at 7.76%. Over the year, the average annualized reduction in electricity consumption due to DST was 2.02%. The study highlights the regional differences in the effectiveness of DST in different cities in Chile. Santiago shows the highest effectiveness, probably due to its energy consumption patterns and daylight availability, as well as Arica, which shows significant benefits, although slightly less than Santiago, and Punta Arenas, which also benefits from DST despite its southern location and unique daylight conditions. In Concepción, on the other hand, DST is very ineffective, possibly due to its latitude, energy consumption habits, or less adaptation to daylight changes. The findings support the implementation of DST as an effective energy saving measure for residential customers, particularly during peak demand periods, and the authors state that these results can guide policy makers in optimizing the DST schedule based on energy consumption patterns [2].

Daniel Flores et al. (2019) [5] examined Mexican residential electricity consumption data from 1982 to 2016, covering a long period before and after the implementation of DST in Mexico in 1996. Their analysis estimated that the introduction of DST resulted in savings equivalent to about 0.5% of total residential electricity consumption. Importantly, the study also finds that the effect of DST is not uniform over time, with savings varying from month to month and possibly even from year to year. This variability indicates that estimates derived from simply extending DST may not fully capture the dynamic or seasonal aspects of how DST affects electricity consumption [5].

Valny Giacomelli-Sobrinho et al. (2022) [49] developed a historical overview of DST in Brazil during different periods: 1931–1933, 1949–1953, 1963–1968, and 1985–2019. Initially, DST was implemented throughout the country, but, from 1988 onwards, it was limited to the southern regions, where the seasonal differences in daylight were greater and DST was, therefore, potentially more beneficial. Initial projections suggested that DST would reduce electricity consumption by around 4% per year, mainly through reduced lighting demand, but the estimated energy savings did not materialize. According to the authors, this shortfall occurred because the DST policy was designed with a focus on lighting and residential use, whereas, in practice, modern electricity consumption in Brazil is driven

more by air conditioning and industrial processes. The gap between the policy goal and the country's evolving energy use patterns ultimately made DST a less effective tool for reducing overall electricity consumption [49].

Fong et al. (2007) [50] investigated the energy-saving potential of DST and Double Daylight Saving Time (DDST) in Japan, focusing specifically on domestic lighting. Despite the absence of DST in Japan, their research provided insights into how adjusting schedules could affect energy consumption. The authors found that both DST and DDST can reduce domestic lighting energy consumption and that the most effective time to implement DST or DDST in Japan is from April to September, coinciding with longer daylight hours and higher domestic lighting demand. Northern Japan benefits more from DDST in terms of reduced energy consumption for home lighting than southern regions. The results underline the importance of designing energy-saving strategies according to geographical and seasonal conditions [50].

Momani et al. (2009) [51] conducted a comprehensive study to assess the impact of DST on electricity consumption in Jordan, using two different analyses. First, a survey of the residential and commercial sectors was conducted to assess the impact of DST on lighting systems. Second, the study analyzed daily load curves to examine total electricity production before and after the implementation of DST in 2000 and 2007. While acknowledging higher energy production requirements due to heating and cooling during DST transitions, the study recommends small reductions in morning electricity consumption. Based on this, the authors suggest that implementing DST within a focused seasonal window (April–August) could optimize energy savings, underscoring the importance of contextual factors such as climate and sector-specific energy use in assessing the overall effectiveness of DST [51].

Karasu (2010) [52] evaluated the impact of DST adjustments on electricity consumption for building lighting in Turkey. Among five scenarios evaluated, the most effective is a 30-minute shift forward to daylight saving time, implemented between April and October. This scenario leads to a maximum saving of at least 0.7% in electricity consumption for lighting [47]. This study complements findings such as those by Mirza and Bergland (2011), which also demonstrate that DST adjustments can yield energy savings [3]. While Karasu focuses specifically on lighting in Turkey, the consistency of results across different regions underscores the broader applicability of DST as an energy conservation measure [52]. In this regard, it is important to emphasize that Turkey's adoption of permanent DST in 2016 reflects a significant shift from its historical practice of periodically aligning with the European Union's DST framework. Indeed, Turkey's periodic adoption of DST between 1916 and 2016 often mirrored European Union practices, with frequent interruptions reflecting shifts in political priorities. In 2016, Turkey adopted the Turkish time zone (UTC+03:00), essentially maintaining DST throughout the year. This eliminated twice-yearly clock changes and brought Turkey's time in line with regions such as Moscow and parts of the Middle East.

In Kuwait, the study by Krarti and Hajiah (2011) [53] shows a nuanced impact of DST on electricity consumption and peak demand, with positive effects in both the commercial and government sectors, likely due to better alignment of working hours with daylight, and negative effects in households and apartment buildings, with a slight increase in energy consumption and peak demand under DST. The authors note that energy consumption across all sectors will increase marginally by 0.07% and peak electricity demand will decrease marginally by 0.14%, equivalent to a reduction of 12 MW based on Kuwait's 2005 peak demand. The construction sector, which accounts for 90% of Kuwait's electricity consumption, plays a significant role in the analysis, suggesting that sector-specific dynamics are central to understanding the overall impact of DST. In short, while the net impact of

DST on energy consumption and demand in Kuwait is minimal, the varied sectoral impacts suggest that policy decisions regarding DST should consider sector-specific behaviors and priorities [53].

Comparison with other studies demonstrates the robustness of these conclusions with the literature review, notably with Belzer et al. (2008), who found similar energy savings from DST implementation and emphasized its role in aligning energy-use patterns with daylight availability to improve efficiency [54], with Kandel and Metz (2001), who highlighted modest but measurable energy savings associated with DST, particularly in regions with pronounced seasonal variations in daylight [55]. Similarly, Niembro and Acosta (1999) reported energy and cost savings associated with DST, confirming the positive impact of shifting daylight hours on energy demand profiles [56], and Hillman and Parker (1988) suggested in early studies that extending DST could lead to both economic and environmental benefits, including reductions in electricity use and carbon emissions [57]. These studies underline that maintaining DST during the winter months offers consistent benefits in terms of energy management, cost efficiency, and environmental outcomes.

Dilip R. Ahuja and D.P. SenGupta (2012) [4] provide a comprehensive discussion of DST and its implications, with insights into its relevance to India. In 1906, Indian Standard Time (IST) was introduced at GMT+5:30, and, in 1942–1945, it was changed to War Time (YRDST), one hour ahead of IST, to conserve energy during World War II. After 1947, IST has remained the official time throughout India, with no use of DST since independence. Based on this, the authors propose that IST be advanced by 30 min (to UTC+6), arguing that this would better match India's daylight patterns and potentially result in energy savings. Advancing IST can reduce electricity consumption, especially in the northern and eastern states where daylight is less optimal. Similarly, aligning with daylight hours can improve productivity and the quality of life by optimizing the use of natural light. The study highlights the importance of tailoring time policies to a country's geographical and social conditions [4].

Sinan Küfeoğlu et al. (2021) [58] focused on the permanent adoption of DST in Turkey since 2016 to assess whether the removal of the biannual clock change has an impact on electricity consumption patterns. By analyzing historical data from 2012 to 2020, this change in DST policy did not lead to a measurable reduction in overall electricity consumption, nor did it produce a consistent, observable daily load shift. Therefore, despite expectations that aligning human activities more closely with daylight hours could save energy, the study conducted in Turkey does not support a significant energy-saving outcome from this policy change. Furthermore, the authors suggest that these findings may be relevant to other countries located between approximately 42° North and 42° South, where similar daylight patterns occur. In short, the energy-saving benefits of permanent DST are not clear in the Turkish context [58].

The study by Choi et al. (2017) [59] provides an in-depth analysis of how DST affects electricity demand in western Australia, using the unique context of a period when DST was implemented and later abolished. Like Karasu (2010) [52] and Mirza and Bergland (2011) [3], this study highlights that the energy-saving benefits of DST are not uniform and depend on the time of day. Unlike studies in regions with colder climates, where DST often reduces morning heating demand, western Australia's warmer climate may exacerbate morning and late evening cooling demand, increasing electricity consumption. The findings of Choi et al. (2017) [59] illustrate the nuanced effects of DST on electricity demand, highlighting the importance of context-specific analysis. While DST can reduce energy consumption during peak evening hours, its overall effectiveness is diminished by increased demand at other times. This study underlines the need for tailored DST policies that consider regional energy patterns and priorities [59].

The impact of DST on energy consumption also varies across commercial building types, reflecting their distinct operational profiles. For office buildings, studies like Grujić et al. (2018) [46] indicate that DST can reduce lighting demand during extended evening hours, though increased cooling needs in warmer climates may offset these gains. In contrast, hospitals, which operate 24/7, experience less pronounced lighting savings due to continuous occupancy, as noted by Eggimann et al. (2023) [48], but face heightened HVAC adjustments to maintain stable indoor conditions amidst shifting daylight schedules. Schools, with daytime-centric operations, benefit more consistently from DST's alignment with natural light, reducing both lighting and heating costs during operational hours. These differences highlight the need for building-specific energy management strategies to maximize DST's potential benefits, a consideration that warrants further empirical investigation.

4.3.3. DST Impact on Energy Demand and Energy Consumption Profile

Grigor'ev V.S. et al. (1984) [60] studied household energy meter readings from 192 apartments in Moscow, Russia, collected between March 1979 and January 1983, to assess how the rational use of daylight under a revised DST schedule affected energy savings and per capita electricity consumption. They found that when the DST period was shifted to cover the period from April to September, measurable energy savings were achieved in these households. This change in the DST schedule appears to have resulted in lower electricity consumption, highlighting how adjustments to clock time can influence daily energy consumption patterns in residential settings. The study suggests that the specific timing of DST implementation, in terms of the months it covers, can have a significant impact on the level of energy savings achieved [60].

Cahit Guven et al. (2021) [61] found that the impact of DST on electricity consumption is not uniform but depends strongly on the ambient weather and the level of air conditioning use for cooling. An early start to DST tends to increase electricity consumption on days with higher temperatures and greater reliance on air conditioning. The study suggests that when weather conditions increase the need for cooling, the extra hour of daylight by shifting activities earlier may not reduce consumption as expected. On the contrary, it may lead to increased use of cooling equipment, increasing overall electricity demand. The research underlines the importance of considering local weather patterns and cooling needs when assessing the energy implications of DST policies and highlights that the energy-saving rationale for DST may be context-dependent and may even backfire under conditions of high temperatures and increased cooling demand [61].

The impact of DST on energy savings varies widely across Europe due to differences in climate and daily activity patterns. In northern and Central Europe, simulations and empirical studies often show that a time shift can reduce electricity demand during peak evening hours by reducing artificial lighting, but in countries with higher summer temperatures, the same time shift can increase electricity consumption by increasing the use of air conditioning, leading to higher energy costs and the additional expense of installing more powerful cooling systems. The impact of summertime on energy consumption is, therefore, highly dependent on local weather conditions and the balance between lighting savings and cooling costs. Given these complexities, the recent EU decision to abolish mandatory clock changes and leave the decision to individual member states reflects the need for each country to weigh its own climatic and economic circumstances when deciding on a permanent time-setting [42,44,62].

According to Çağatay Bircan and Elisa Wirsching (2023) [63], when Turkey switched to permanent daylight saving time in October 2016, the daily load profile changed significantly, with electricity consumption increasing in the early morning and decreasing in the late

afternoon. This redistribution of demand meant that during peak hours, generation shifted away from the most polluting fossil fuel plants towards cleaner renewable sources, with hydropower playing a key role. As a result, although total energy consumption did not fall, the change in load timing led to lower emissions from electricity generation [63].

5. Conclusions

Based on the literature review, the impact of DST on energy consumption is controversial. The applied studies have produced limited, incomplete, and, in some cases, contradictory results, mainly because they often do not fully consider economic, geographical, climatological, and behavioral factors. In general, the benefits of DST are highly site-dependent, with regions showing very different responses depending on their local climate and daylight profiles. Regarding energy efficiency, our review indicates that DST yields modest reductions in lighting-related electricity consumption in commercial buildings, particularly in regions with significant seasonal daylight variations, though these savings may be offset by increased HVAC demand in warmer climates. To optimize energy use, building managers should implement adaptive lighting controls that adjust to extended daylight hours during DST and enhance HVAC scheduling to mitigate cooling spikes in summer. For occupant comfort and productivity, the disruption of circadian rhythms suggests a need for flexible work hours in the weeks following time shifts, allowing employees to adjust to altered daylight patterns. Operationally, automated building management systems (BMSs) should be recalibrated biannually to align with DST schedules, ensuring efficient energy distribution and maintaining thermal comfort. These strategies can collectively enhance energy efficiency and occupant satisfaction in commercial settings under varying daylight regimes. On the other hand, the impact on occupant comfort and productivity of changing schedules can disrupt circadian rhythms, affecting sleep quality, productivity, and occupant well-being. Discrepancies between social time and solar time can have negative effects on health and work efficiency, especially in the first weeks after the time change. Despite the insights provided, this study faces limitations that temper its findings. The reliance on bibliometric and systematic review methods limits our ability to generate primary data specific to commercial buildings, while the heterogeneity of regional studies complicates universal conclusions. Additionally, the evolving adoption of energy-efficient technologies, such as LED lighting, may reduce DST's relevance, a factor not fully captured in older studies. Future research should prioritize localized, empirical studies using high-resolution energy load data from diverse commercial building types, particularly in understudied regions like Africa and Asia. Integrating occupant feedback through surveys could further elucidate comfort impacts, while longitudinal analyses could assess how technological advancements alter DST's efficacy over time. Such efforts would refine our understanding of DST's role in building management and inform evidence-based policy decisions. Nevertheless, transitioning to more stable schedules aligned with natural sunlight patterns may be more beneficial in terms of public health and energy efficiency. As future work, it is recommended that a comprehensive study be undertaken to assess the impact of DST on electricity demand by analyzing the load diagrams of different buildings both before and after the DST transition. By combining this high-resolution load data with precise sunrise and sunset times, it will be possible to better isolate the effects of DST from other variables and gain a clearer understanding of how the clock shift affects both peak and total energy demand. This approach will help fill current knowledge gaps and provide a more nuanced picture of how and why DST affects energy use in different environments. However, moving to more stable schedules that align with natural sunlight patterns may be more beneficial in terms of public health and energy efficiency.

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