A Comprehensive Analysis of Sustainable Energy Development: A Review of Existing Research

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Abstract. This study delves into the complex world of sustainable energy development, seeking to distil the essence of this multifaceted concept. We uncover the key aspects and activities that underpin sustainable energy development through a meticulous and systematic review of existing literature. Our research journey begins with analysing

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publication trends and tracing the chronological trajectory of scholarly output on sustainable energy development. We identify the most influential articles in the field based on citation frequency and map the global research landscape, pinpointing the top contributing countries.

Next, we explore the dominant subject areas and disciplines intertwined with sustainable energy development and provide a comprehensive overview of the diverse definitions and interpretations surrounding this concept. Our study highlights the pivotal activities and initiatives driving sustainable energy development. Ultimately, our research reveals that achieving sustainable energy development hinges on three critical actions: transitioning to renewable energy sources, boosting energy efficiency, and mitigating greenhouse gas and air pollutant emissions. Notably, our findings underscore the need for a unified definition of sustainable energy development, highlighting the need for further research and clarity in this field.

Keywords: SED; Energy Efficiency; Renewable Energy; Greenhouse gas emission; Low carbon economy.

INTRODUCTION

The energy sector has been the backbone of human civilisation since the Industrial Revolution, fuelling progress and development. However, its dark underbelly is now apparent: it's the primary source of greenhouse gas emissions, with the European Union attributing nearly 80% of these emissions to this industry [1]. The writing is on the wall - we need to rethink our energy paradigm. Sustainable Energy Development (SED) has emerged as a beacon of hope, promising a cleaner, greener future. The concept has gained significant traction recently, with researchers and policymakers recognising its importance [2, 3, 4]. SED is not just a buzzword; it's a clarion call to action, urging us to transition to alternative energy sources, boost energy efficiency, and mitigate emissions [5].

The imperative for SED is clear. Climate change, energy security, and economic sustainability are inextricably linked, and the energy sector is at the nexus of these challenges [6]. The United Nations' Sustainable Development Goal 7 (SDG 7) aims to ensure universal access to affordable, reliable, and modern energy by 2030, underscoring the global commitment to SED [7].

Despite the growing body of research, SED remains a nascent concept, crying out for a stronger theoretical foundation. The lack of a unified definition, disparate research focus areas, and inadequate understanding of SED's implications hinder its widespread adoption [8, 9, 10].

This study addresses this knowledge gap by presenting SED's comprehensive systematic literature review (SLR). We'll delve into the concept's definitions, key activities, and future research directions, providing a roadmap for scholars and practitioners seeking to make a meaningful impact.

Following the guidelines, this study employed a systematic approach to ensure a comprehensive and unbiased literature review. Systematic literature reviews (SLRs) identify consistent themes by analysing previous studies' findings. Originating in the medical sciences in the 1970s, SLRs have been applied to various disciplines, including computer science, engineering, business, physics, mathematics, and the arts and humanities.

SLRs differ from traditional narrative reviews by adopting a transparent, scientific, and replicable process. Critical features of SLRs include a clear set of objectives, explicit methodology, systematic search, and presentation of findings.

While meta-analysis is another approach to literature review, it requires a mature research topic with sufficient homogeneous studies. Given the nascent state of sustainable energy development (SED) research, an SLR was deemed more suitable.

The research questions guiding this SLR were: 1) What is the current state of research on SED? 2) What are the most critical activities within SED? 3) What are the future research directions related to SED?

The literature search was conducted on March 20, 2024, and the inclusion criteria consisted of peer-reviewed journal and conference papers written entirely in English focusing on SED.

RESULTS AND DISCUSSION

Quantitative approach

This part of the study will present quantitative results. The authors will present the distribution of articles on the SED concept by year. They will also identify the most cited articles, the countries (and their research units) with the most significant contribution to the SED publication activity, and the subject areas with which the analysed articles correspond. Thus, the following questions will be answered: 1) What is the current state of the research on the SED?

The concept of Sustainable Energy Development (SED) first gained prominence in 1992, coinciding with the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro [11]. This conference led to the adoption Agenda 21, which emphasised the interconnectedness of environmental and economic development [12]. As a result, SED became a central focus of environmental and development policies [13].

Initially, publications on SED were scarce, with only a handful of journal and conference papers appearing until 2005 [14, 15, 16]. However, from 2006 onwards, there was a significant surge in publications, exceeding 10, 20, and 30 per year in subsequent years (Scopus database, 2006-2014). The European Commission's green paper on climate and energy policy in 2013 [17] and the Paris Climate Agreement in 2015 [18] further accelerated the growth of SED-related publications.

According to the Scopus database, the number of publications on SED has been increasing rapidly since 2015, reaching 80 in 2021 (Scopus database, 2021). Journal articles have consistently outnumbered conference papers, with an average of over three times more published than conference papers over the past thirty years (Figure 1).

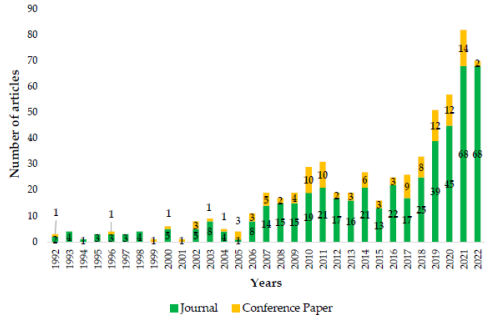

Figure 1 – Distribution of Articles by Year

The most influential research papers on Sustainable Energy Development (SED) are highlighted in Table 1. The most cited article, with an impressive 1645 citations, is a ground-breaking study [19]. The paper was published in the prestigious journal "Nature Materials" in 2012 and explores the development of rechargeable sodium batteries using earth-abundant elements. The authors emphasise the crucial role of rechargeable batteries in driving green development and SED, particularly in the context of electric vehicles, which are increasingly replacing traditional internal combustion engine cars.

Table 1 – Most frequently cited publications

Citation count	Publication Year	Authors
427	2009	[20]
312	2015	[21]]
284	2007	[22]
221	2007	[23]
210	2003	[24]
197	2008	[25]
196	2010	[26]
191	2014	[27]
189	2011	[28]

The second most influential paper on Sustainable Energy Development (SED) is "Potential contribution of biomass to sustainable energy development" [20]. This study explores biomass energy's global potential and historical evolution, highlighting its significance in SED. Another notable paper is "High-capacity electrode materials for rechargeable lithium batteries" [21], which received 312 citations. This conference paper presents a novel lithium battery system with a cation-disordered rocksalt structure.

Regarding publication activity, China leads the way, accounting for 24% of SED-related publications, followed by the United States (over 10%). Prominent research centres in China include the Chinese Academy of Sciences and Tsinghua University, while in the US, the University of Pennsylvania and the University of Delaware are vital players. Other leading countries in SED research are Turkey, India, Lithuania, and Poland, with notable research centres including Karadeniz Technical University, Anna University, and Silesian University of Technology.

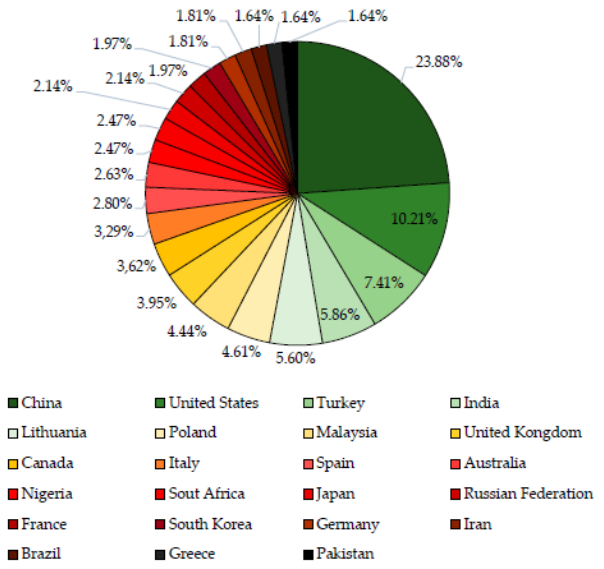

Figure 2 – Article per Country

The research areas of the publications in the Scopus database were diverse and interdisciplinary, spanning 22 fields (Figure 3).

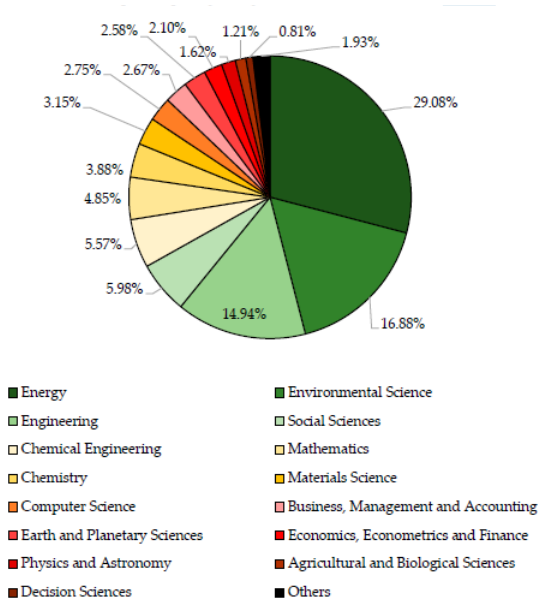

Figure 3 – Article per Course

These areas included Energy, Environmental Sciences, Engineering, Earth Sciences, Social Sciences, Economics and Finance, and Agricultural and Biological Sciences. Some publications belonged to multiple research areas, such as the article by [47], which was classified under Energy, Environmental Science, and Engineering.

Energy was the most extensive research area, accounting for approximately 30% of the total publications (360 articles). This indicates energy research's significance and ongoing development across various disciplines and periodicals. Environmental Sciences and Engineering followed, with 17% (132 publications) and 15% (185 publications) of the total volume, respectively.

Specific fields, such as Medicine, Psychology, Immunology, Neuroscience, and Pharmacology, had a relatively small representation, with less than 1% of the total publications.

Qualitative Approach

In this part of the study, the authors will showcase qualitative findings featuring a curated selection of definitions related to Sustainable Energy Development (SED), including their proposed definition. Additionally, they will highlight the key activities and initiatives undertaken under the umbrella of the SED concept, emphasising their significance and impact.

Sustainable Energy Development (SED). Numerous researchers, including [5], have attempted to clarify the concept of Sustainable Energy Development (SED). Table 2 presents a compilation of SED definitions from the analysed publications. It is important to note that these definitions were the only ones identified in the included publications. However, some authors referenced definitions from reports outside this systematic literature review (SLR) scope. Despite these efforts, a unified definition of SED still needs to be discovered.

The concept of sustainable energy development (SED) is context-dependent, and its meaning can vary depending on the research context and objectives [5]. This variability highlights the need for a clear and unified definition of SED. The authors of this article aim to contribute to the theoretical development of SED through a systematic literature review, providing a comprehensive foundation for future research and facilitating a clearer understanding of the concept. By clarifying the definition of SED, this review hopes to contribute to sustainable energy development.

Table 2 – Definition of SED

Authors	Definition	Citation count
[29]	The mission to address the issues for SED is to enhance	18

Authors	Definition	Citation count
	the capacity of concerned stakeholders in developing sustainable development strategies under which energy services can be expanded and improved with a minimum compromise on environmental quality. Due weight must be given in focusing on poverty alleviation, equity and social justice.	
[30]	Renewable energies are considered as an essential element of any strategy for SED. The poor in the developing world without access to modern energies are regarded as a major market for renewable energies	10
[31]	SED is satisfying the energy needs of the present generation without compromising future generations in satisfying these same needs. It encompasses three areas: economy, environment and society. Sustainable energy production can be accomplished through energy efficiency and renewable energy sources, among others.	8
[32]	A vital part of sustainable development is providing adequate, reliable, and affordable energy, in conformity with social and environmental requirements.	8
[33]	SED can be assessed by analysing the decoupling of GDP (Gross Domestic Product) from energy consumption and the decoupling of energy consumption from atmospheric pollution, including GHG (Greenhouse Gas) emission.	26
[34]	SED is an energy system that serves the needs of the present without harming the needs of future generations. The major sources of SED are renewable such as hydroelectricity, solar energy, wind energy, wave energy, geothermal energy, bioenergy, tidal energy.	0
[35]	SED has come to mean the harnessing of those energy sources that meet three requirements: (1) they are not significantly depleted by continued use; (2) they do not entail the emission of pollutants or other hazards to human or ecological and climate systems on a significant scale; and (3) they do not involve the perpetuation of significant social injustices.	12
[36]	"SED can be understood as socio-economic development due to energy services provided at affordable prices in a safe and environmentally friendly manner".	12
[37]	Seven major areas are listed with specific problems and their relevance to the SED: energy resources and development; efficiency assessment; clean air technologies; information technologies; new and renewable energy resources; environment capacity; mitigation of nuclear power threat to the environment".	110

The definitions presented in this study were sourced exclusively from articles that met the authors' criteria and were indexed in the Scopus database. Consequently, relevant definitions from books, book chapters, monographs, or reports were excluded. Notably, the Scopus database needed more theoretical papers that comprehensively explained the complexity of Sustainable

Energy Development (SED). The authors have proposed their definition to address this gap, positing that SED is a fundamental concept and a pillar of sustainable development. This definition encompasses three key aspects: ensuring universal access to energy, promoting affordable energy, and balancing environmental sustainability with social and economic development. Activities that serve to implement the SED include increasing the use of alternatives, including renewable energy sources in the energy mix, enhancing energy efficiency, and reducing emissions of greenhouse gases and air pollutants. A graphical interpretation of this concept is shown in Figure 4.

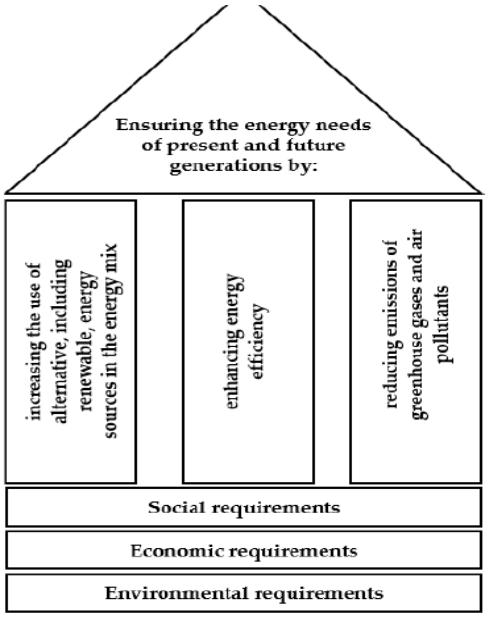

Figure 4 – Sustainable energy development

Use of Renewable Energy Sources in the Energy Mix. The first of the pillars of the SED is to increase the share of renewable energy sources in the energy balance. These include wind energy, solar radiation, geothermal energy, hydrothermal energy, hydropower, the energy of waves, currents, and tides, and energy obtained from biomass, biogas, agricultural biogas, and bioliquids.

Several studies, for example, [38, 39, 40, 41] were conducted on the use of solar and wind. There also exists a considerable body of literature on biomass consumption, including [42, 43, 44]. A number of researchers [45, 46] discussed the topic of the use of biogas. Finally, an interesting approach to the use of renewable energy sources in terms of hydropower was presented by [47, 48] among others. It's essential to note that the EU has set stringent standards for adopting renewable energy sources (RES) technologies, and for good reason.

As shown in Table 3, the benefits of transitioning to RES are substantial, with far-reaching positive impacts on society and the environment.

Table 3 – Social and environmental benefits of renewable energy sources

Type of Benefit	Example
Environmental	_ reduction of pollution of the lithosphere, hydrosphere, and atmosphere; _ the ability of self-regeneration of the regional natural environment; _ regional determination of the absorptive capacity of the environment and the state of its resources (in quantitative and qualitative terms); _ introduction of a reliable, comprehensive environmental assessment; _ the ability to manage protected areas without harming the lives of their inhabitants
Social	improvement of social welfare and, at the same time; _ participation of residents in public life; _ maintaining local traditions; _ knowledge creation and transfer; _ stimulating economic, financial, and legislative support mechanisms for actions for renewable energy in the region and creating incentive systems for energy prosumers; _ ensuring equal access to renewable energy technologies as well as their products from the poly-generation energy portfolio.

Improvement of Energy Efficiency. Promoting energy efficiency is a crucial pillar of Sustainable Energy Development (SED). In the 1970s and 1980s, energy efficiency emerged as a primary concern, and despite fluctuations in oil prices, environmental concerns persisted, particularly with the growing debates on global warming and climate

change. By the 2000s, energy efficiency had become a top priority on the political agenda of many countries, driven by soaring oil prices and the need to address climate challenges. Today, improving energy efficiency is an option and an opportunity for cities and investors to promote competitiveness and mitigate climate risks.

However, the increasing uncertainty in the global political and economic landscape has heightened the need for countries to adapt their policies to changing circumstances. Economic policy uncertainty (EPU) has become a significant concern, as it can impact economic activity, energy supply and demand, investment, technological development, and individual energy consumption.

As the world shifts towards sustainable development, governments globally acknowledge energy efficiency's vital role in achieving this goal. Energy efficiency now encompasses the responsible use of energy resources and addressing wasteful and harmful consumption patterns that impact consumers and the environment. Ensuring energy security and sustainable development is closely tied to a country's economic growth.

To enhance energy efficiency, sustainable and interconnected energy sources can be leveraged. For instance, combined heat and power (CHP) systems generate electricity and heat more efficiently than separate systems. Integrating nuclear energy, particularly from small modular reactors, is also gaining traction to optimise cogeneration processes. Furthermore, polygeneration systems, which produce multiple types of energy simultaneously, offer a promising alternative for achieving energy and environmental objectives. These systems are increasingly being adopted in buildings, where they can provide combined electricity, heat, and cooling. Renewable energy technologies play a pivotal role in poly generation systems in residential buildings, driving the transition towards sustainable energy solutions.

Reduction of Greenhouse Gas Emissions and Air Pollutants. Research on reducing greenhouse gases and air pollution tends to concentrate on five key areas: developing innovative energy solutions, Decreasing CO_2 emissions from transportation, Implementing pollution taxes or levies, Establishing emissions trading systems, and Enhancing natural carbon sinks through sustainable land use and forestry practices.

One of the primary research challenges is introducing innovative energy solutions, which have been explored in numerous studies. Given the ambitious goals of climate and energy packages, these analyses have highlighted the difficulties of reducing greenhouse gas emissions in EU countries. Achieving these goals will require significant effort from EU countries. To transition to sustainable energy systems, governments must adopt new concepts that promote using renewable energy sources and improve energy efficiency. Researchers have also investigated the link between innovation and CO_2 emissions. A study by [46] found that innovations in renewable technologies can significantly reduce CO_2 emissions, with benefits extending beyond regional boundaries. Another crucial aspect is the impact of transportation innovation, particularly as economies shift towards digital technologies.

Additionally, studies have examined the implementation of innovative energy technologies in road transport, such as electric and hybrid vehicles, which offer the most effective solution for mitigating the negative environmental impacts of transportation. However, the adoption of these technologies varies across EU countries, with Sweden, the Netherlands, and Finland leading the way. Ecological taxes have emerged as a crucial strategy for mitigating the adverse effects of external environmental pollution. According to [41], these taxes are the most influential economic instruments in EU countries for reducing the environmental impact of various financial activities. By implementing ecological taxes, governments aim to encourage reducing fossil fuel consumption and adopting renewable energy sources or low-carbon fuels, ultimately decreasing pollution.

Research has examined the socio-political responses to environmental tax reform in European countries, revealing that while ecological tax reform is widely regarded as desirable, its implementation is hindered by political acceptance issues, including awareness, trust, and understanding of the goals and taxation levels. To address this, suggest publicly presenting the advantages and disadvantages of taxation to gain acceptance from entrepreneurs and the general public. The benefits of environmental taxes extend to promoting sustainable energy development, influencing the adoption of renewable energy sources, energy intensity, and GHG emission factors. These taxes also encourage implementing advanced technologies, improving energy production processes, and enhancing competitiveness, environmental sustainability, and energy security, ultimately

contributing to reduced air pollution, climate change mitigation, and improved quality of life.

Recent research has explored the impact of environmental taxes on ecological footprint transfers between countries, revealing that countries with an ecological deficit face challenges in managing their energy resources. Furthermore, [3] found that environmental taxes can offset the increase in ecological footprint resulting from economic growth in OECD countries. The EU Emissions Trading System (EU ETS) is another vital tool for reducing greenhouse gases, with researchers identifying critical challenges in emissions trading, including pricing models, specialised traders, and organisational structure.

CONCLUSIONS

This study has made significant strides in understanding Sustainable Energy Development (SED) by conducting a comprehensive literature review. Despite some limitations, including reliance on a single database and language constraints, we achieved four key objectives: 1) Analysed publication trends and patterns in SED research; 2) Identify influential and frequently cited articles shaping the field; 3) Determine top contributing countries to SED research; 4) Uncovered associated subject areas, revealing SED's interdisciplinary nature.

Our research yielded valuable insights into SED's current state, essential implementation activities, and future research trends. We developed a conceptual model for SED, emphasising universal access to energy in an environmentally sustainable and socially responsible manner. Three critical activities for implementing SED were identified: increasing alternative energy sources, enhancing energy efficiency and reducing emissions.

Our study highlights the need for a universally accepted SED definition and notes that relevant publications were overlooked due to missing keywords. To further advance SED understanding, we propose validating our conceptual model to explore implementation factors and their impact on security and social welfare.

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