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Review

# Trends for Stirling Engines in Households: A Systematic Literature Review

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**Abstract:** Reliable heat and power supply are among the basic household needs nowadays. It is especially topical in rural or distant locations that may be cut off from the energy grid due to extreme weather or other events. Nonetheless, the sustainability of our power production systems has to be considered to sustain our planet's long-term abilities to provide energy resources and a viable environment. Renewable energy resources must be prioritized in rural and remote areas, simultaneously strengthening distributed production ability and self-sufficiency. In this context, the use of the Stirling engine for heat to power generation in households, on the scale of small communities, and by using only renewable resources is becoming increasingly topical. Therefore, this research aims to identify the current state-of-the-art for Stirling engine applications using biomass as a renewable energy source, in the context of sustainability and energy security. The paper summarizes the current research tendencies at the household level in the use of biomass-based Stirling engines for renewable heat and power generation in decentralized energy systems. The methodology applied is a structured literature review and content analysis. The research results corroborate the progress towards the use of renewable resources and towards increased energy efficiency because the keyword and overlay analysis showed more frequent publishing in these areas. The content analysis on two more specific sub-directions of interest, i.e., biomass-fuelled Stirling engine use in households and Stirling engine implications on energy security, showed that though research activity in these directions has increased lately, more profound research is needed, especially on aspects of energy security and independence. The content analysis revealed a lack of in-depth analysis on the effects of Stirling engine use on energy security or energy independence, which is suggested as a topical subject for future research.

**Keywords:** Stirling engine; residential; household; biomass; micro-CHP; energy security; renewable electricity; structured literature review; keyword analysis



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## 1. Introduction

With the objective of tackling climate change, the European Union has set ambitious aims to improve energy efficiency, increase the renewable energy share, and reduce greenhouse gas emissions [1]. Meanwhile, the actual effects of climate change are becoming more evident and producing, among other disturbances, power failures and outages due to more intense flooding, storms, and other extreme weather events. Energy availability, security, and energy independence are currently equally important points on the agenda of every EU Member State, especially since the start of Russia's war in Ukraine in 2022. The EU also emphasizes that the energy transition must be just and such that would not negatively impact the vulnerable groups in society. The EU Social Climate Fund has been created to aid vulnerable households and engage against energy poverty [2].

Although worldwide electricity access is improving, it is estimated that by 2030, 675 million people will still lack access to electricity [3]. Rural communities are one of those potentially exposed to risks of energy security and supply continuity. The shift towards renewable energy sources can improve regional resilience and independence from fossil fuels [4], and localized energy generation is economically advantageous and promotes sustainability [5].

Lately, there is an increasing trend in the development of distributed energy generation systems [3,6]. The increase in popularity is mainly due to reduced prices of the technology, resulting in increased technology availability [7], advantages in comparison to central generation [3], and, in some cases, the necessity to ensure energy availability and security [8]. On top of that, Chmielewski et al. [9] predict a dynamic development of prosumer micro-installations until 2030. Prosumers are the energy end users who are also able to generate energy and supply it to the grid or heat networks [10], and they can play a significant role in the development of decentralized sustainable energy systems [11]. Hence, the possibilities and opportunities for households, especially rural ones, to increase their renewable energy share provide a topical research direction.

The most popular technologies used for distributed and decentralized energy generation are solar panels for power production, solar collectors, and biomass boilers for hot water production and heating. However, solar-based technologies are always constrained by favorable weather conditions [12]. Biomass can be used as fuel in co-generation technologies, which, in addition to simultaneously providing heat and power, can also provide a significant increase in process efficiency (30–35% to 80% [13]). Energy technologies can be classified by electric capacity: micro-CHP (up to 50 $kW_{el}$), medium power CHP (50 $kW_{el}$ to 1000 $kW_{el}$), and large-scale CHP (>1000 $kW_{el}$) [14]. The maximal thermal capacity of micro-CHP is 300 $kWh_{th}$ [15]. The literature provides various decentralized combined heat and power production technologies, including fuel cells, Organic Rankine cycle (high or low temperature), and Stirling engines [9,15]. İncili et al. [16] emphasize the advantages of the Stirling engine for residential users in rural areas which lack electricity infrastructure, for example, independence from power cuts and increasing energy security. Surdacki et al. [17] note that systems with a Stirling engine can provide energy independence for households and even the potential to resell surplus energy. Alanne and Saari [18] state that Stirling engines are very applicable on a residential scale because of their suitable electricity-to-heat ratio. This can be a significant criterion, especially in rural areas in colder climates. Abuelyamen and Ben-Mansour [19] used computational fluid dynamic simulation to compare the efficiency and output of various types of Stirling engines under similar conditions and determined that the highest power output (9.22 W) and thermal efficiency (9.8%) are for $\gamma$-type Stirling engines, then $\beta$-type and $\alpha$-type (accordingly, 8.7 W; 7.5% and 0.9 W; 1.8%). For an energetic efficiency and price function comparison between Stirling engines and other systems for heat conversion to power, see [20]. The current study focuses on Stirling engine technology to assess the previous development of studies in this area and to gauge the future research tendencies in the context of sustainability and energy security. There have been literature reviews that consider Stirling engines [13]; however, there is no structured literature review available concerning Stirling engine technologies, particularly in the context of sustainability and with the aim to increase the renewable energy resource share and energy security.

Thus, the aim of this research is to identify the current state-of-the-art for Stirling engine applications using biomass as a renewable energy source, in the context of sustainability and energy security. To achieve that aim, we performed a structured literature review focusing on scientific literature and identified the past and future research tendencies, considerations of sustainability and energy security in the current geopolitical, economic, and climate change context.

## 2. Materials and Methods

As information availability and open-access knowledge repositories continue to expand, and the size of their stocks increases, more efficient and systematic literature review methods have become indispensable. This research adopts the Structured literature review methodology. Structured literature review allows identifying significant research trends and the state-of-the-art in the considered field [21]. By first providing a systematic method for the assessment of available sources, Structured literature review then proceeds to analyze the content of the most promising papers, thus incorporating elements of both bibliometrics and literature review.

The Structured literature review method has been previously applied to analyze various aspects of energy systems, i.e., energy efficiency in buildings [22,23], renewable energy sources [24,25], smart grids [26]. Literature analysis on Stirling engine applications has been published, i.e., [13] reviewed cases of biomass-fueled Stirling engine applications and solar-based Stirling systems [27]. Some of these reviews have applied a structured research methodology (see [27]), but have not considered aspects of sustainability and energy security as central questions. Also, no structured literature review, particularly concerning Stirling engine applications using biomass, was previously identified.

In the Structured literature review process, first, the literature review protocol has to be developed [28], and one of its initial steps is the formulation of research questions (RQs) [29]. According to Structured literature review methodology descriptions [21,28], the RQ can be derived in three main directions: (1) an assessment of the overall development of the study area; (2) more specific development trends particularly concerning the research focus area; (3) research implications in the study area. Taking into account the topicality mentioned in the introduction, the three main RQ development directions above, the following RQs are elaborated for the structured literature review on biomass-fueled Stirling engine applications that may increase renewable energy share, energy security, and sustainability:

RQ1: How has the Stirling engine literature developed over time?

RQ2: What is the focus and the latest tendencies in small-scale (residential) renewable energy-based Stirling engine research, with a particular focus on biomass?

RQ3: What are the implications of the Stirling engine in terms of energy security, energy independence, and environmental research fields?

The developed research protocol (see Figure 1) describes the process applied and includes the methods used to choose information sources (database), select the particular studies for analysis, explore and summarize them [21,30]. According to Massaro et al. [28], "it is important to understand, that all research is a journey and not a strict series of events", thus there is circularity and iteration involved, which is also depicted in the research protocol. The advantages of introducing circularity into the literature review process include the ability to profoundly explore the background of the topic and to account for the rapid changes in the field of research [31,32]. We have thus devised a sequential and structured literature review process that also incorporates a degree of circularity and iteration.

Previous studies have indicated that the Scopus database is superior to Web of science in terms of coverage for engineering studies [21,32]. According to the database evaluation approach taken by Nolting et al. [32], in Step 2 of the methodology, we compare the coverage of Scopus and Web of Science, the two most popular scientific publication indexes. The top 100 journals in 2022 (latest available data) for the subject area "Energy" and subject category "Energy Engineering and Power Technology" were identified from Scimago journal rankings [33]. It was then identified which of those journals are available in each of the two databases. As a result, Scopus coverage in this context is determined to be 100%, as all 100 top journals were indexed in Scopus. For Web of Science, only 84 of the top 100 journals were represented in the database, thus the coverage of 84% can be assumed. The journals covered by Scopus but not Web of Science included some journals published predominantly in Chinese, and a few journals based in the UK, USA, Netherlands, and

Switzerland. There were no journals in the selection that were included in the Web of Science database that were not available in the Scopus index. The results of Step 2 of the research protocol confirm that (similar to previous conclusions from the literature [21,32]) in the particular research topic, the Scopus database coverage is wider regarding Scimago Top-ranked journals. Therefore, the Scopus database is chosen for document retrieval. The document retrieval was performed in October and November 2023.

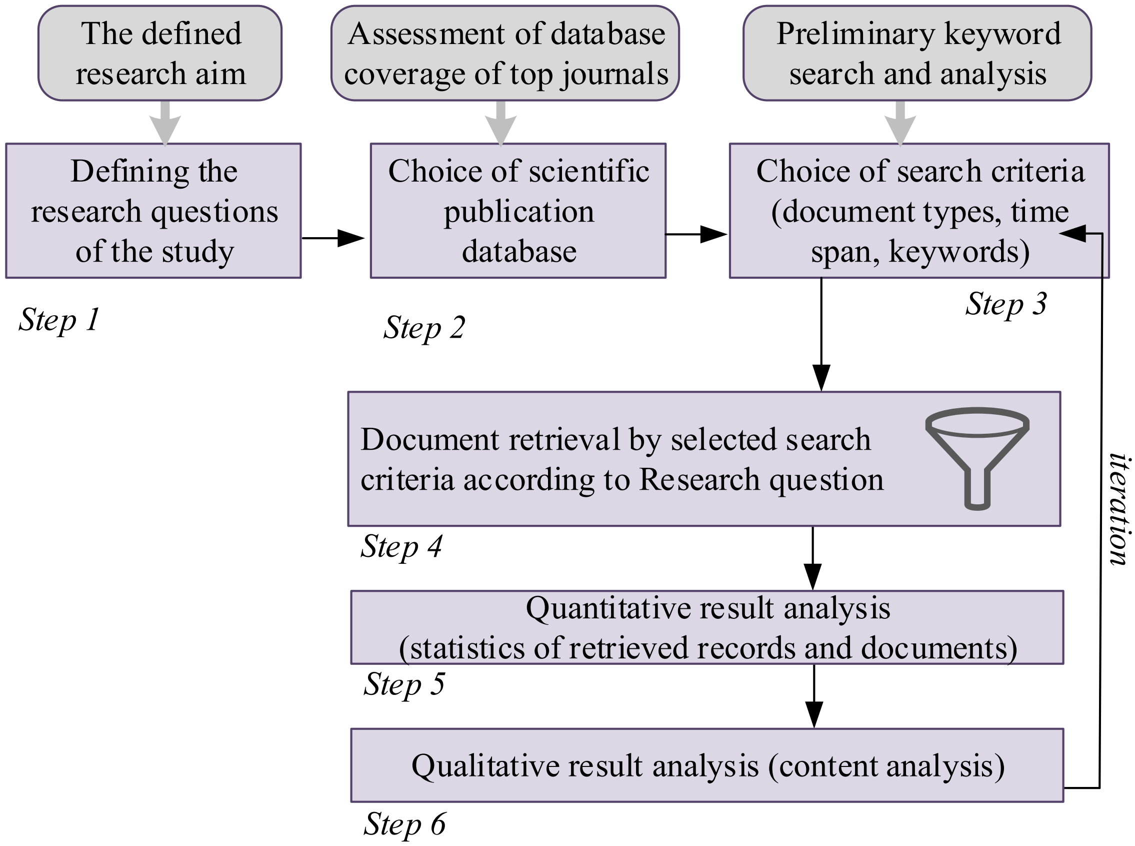


**Figure 1.** Applied research methodology.

Step 3 is the selection of search criteria to filter the whole literature basis. Nolting et al. (2018) integrated three searching techniques—keyword searching, backward searching, and forward searching. We adopt this approach—first, for the initial keyword generation and analysis, the literature in the respective research area is analyzed, followed by backward and forward searching to improve the search criteria. The most general keyword, "Stirling engine", was used for the preliminary search (considering Article title, Abstract, Keywords), producing 4213 results in Scopus (see Figure 2) between 1960 and 2023. Almost 88% of the hits were in English, while the others were in Chinese, Japanese, German, and other languages. The number of publications has increased significantly since 1977 and peaked in 1984. The period 1984–1993 shows a highly variable but generally downward trend, indicating that Stirling engine research declined in importance during this period, but after 2002, there was a resurgence of interest in Stirling engines, with a peak point of 199 articles in 2021. Overall, there has been a significant fluctuation in the number of Stirling engine publications over time. If the literature body is assessed by the publication type, Figure 2 indicates that the increased scientific interest in the 1980s was driven mainly by conference papers, while in the last two decades, a significant increase in journal articles is seen. The above-mentioned sample of 4213 documents was retrieved by including all document types. It was decided to further limit the search to only consider articles, conference papers, and reviews, and exclude conference reviews and books as they are not original research papers, and conference reviews are summaries of conference topics and have no specific authors.

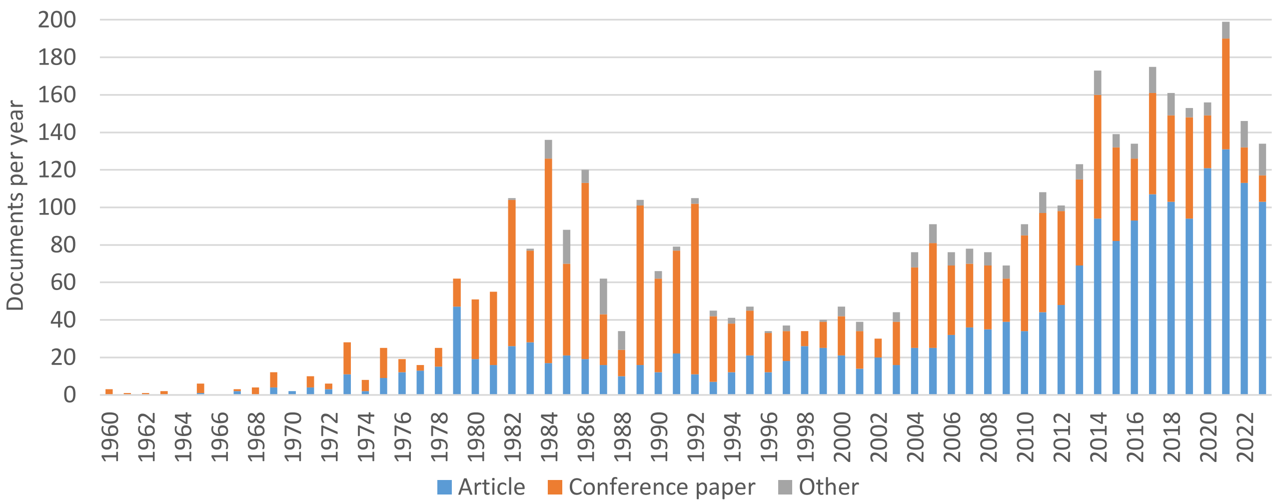


**Figure 2.** Dynamics of publications mentioning "Stirling engine" divided by document type (data source: Scopus database).

The statistics of the initial search provide the top keywords obtained in the results. Excluding close duplicates, the top ten Stirling engine co-cited keywords are: heat transfer, heat engines, solar energy, regenerators, thermodynamics, air engines, pistons, free piston Stirling engine, energy conversion, optimization. In comparison, in the most recent publication period (since 2002), 'solar energy' is even higher in the top 10 keywords, while renewable energy resources (or sources, energies), biomass, and sustainable development are mentioned 101, 84, and 28 times, respectively.

Considering the previously stated research aim and questions (see Step 1), the advanced search was done with several extended search strings (see Table 1), but also trying not to superimpose keywords that were too narrow. The elaboration of presented research strings for each consecutive RQ was not performed in a linear approach, but instead, the above-mentioned circularity and iteration approach were applied (represented in Figure 1 with feedback/iteration loop). RQ1 was investigated by quantitative analysis of the statistics of the acquired sample (methodology Step 5). For RQ2 and RQ3, firstly, the sample statistics were assessed (Step 5), then titles and abstracts of the retrieved documents were screened and analyzed, followed by content analysis (Step 6), and at these stages, four reviewers were involved. The inclusion bias was limited by screening and analyzing the abstracts of all retrieved records. Most records were retrieved and analyzed also as full papers (for RQ2 ($n$ = 34) and RQ3 ($n$ = 8)).

**Table 1.** Search criteria for each of the defined research questions.

| Research Question | Search Criteria | |
|---|---|---|
| | **Search String** | **Description** |
| RQ1 | TITLE-ABS-KEY ("stirling engine")<br>AND<br>PUBYEAR > 1959 AND PUBYEAR < 2024<br>AND<br>(LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re")) | All available time series data, limited to Article, Conference Paper, Review<br>Time series until November 2023 |

**Table 1.** *Cont.*

| Research Question | Search Criteria | |
|---|---|---|
| | **Search String** | **Description** |
| RQ2 | (TITLE-ABS-KEY ("stirling engine")<br>AND<br>TITLE-ABS-KEY ("residential" OR "household" OR "micro combined heat and power" OR "micro cogeneration" OR "micro-CHP" OR "micro-cogeneration" OR "micro-combined heat and power" OR "microcogeneration" OR "micro-generation")<br>AND<br>TITLE-ABS-KEY ("biomass"))<br>AND<br>PUBYEAR > 1959 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re")) | Constraints applied in RQ1 plus keywords to select publications concerning household scale technologies and biomass-fueled technologies |
| RQ3 | (TITLE-ABS-KEY ("stirling engine")<br>AND<br>TITLE-ABS-KEY ("energy secur*" OR "energy independ*"))<br>AND<br>PUBYEAR > 1959 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re")) | Constraints applied in RQ1 plus keywords to select publications concerning energy security and energy independence |

## 3. Results

Within this section, first, a quantitative analysis of the sets of publications obtained by each of the three research queries is provided. Then, the qualitative content analysis is provided, with a particular focus on RQ2 and RQ3 where the sustainability and energy security aspects are considered.

### *3.1. Quantitative Analysis*

The quantitative literature analysis must ensure the quality, completeness, and relevance of the assessed articles [32]. The summary of the quantitative results for all three RQs are shown in Table 2. The dedicated search string for RQ1 led to a sample of 3997 articles used to investigate and justify RQ1 through a quantitative analysis of the statistics of this sample.

Since the discovery of the Stirling engine in 1816 up until today, the technology has been researched from time to time increasingly and at other times at a lower intensity to find even more efficient modes of application [34]. A particular increase in development has been seen in the last 50 years [35]. To understand how Stirling engine literature has developed, keyword analysis was conducted. Figure 3 shows the timely dynamics of other topical keywords used in publications in combination with the obligatory keyword "Stirling engine". It can be seen that, during the earlier period for which publishing records are available, "air engine" (as in hot-air engine) was a significant keyword used together with "Stirling engine" with numerous mentions (97% of articles with this combination were published between 1969 and 1994).

In the retrieved articles, various terms are used as keywords relating to solar technologies, i.e., dish Stirling, concentrated solar power, solar concentrators, solar energy, solar heating, solar power, solar power generation, solar power plants. To avoid double counting, these are all analyzed in combination (see "solar" in Figure 3). While papers including solar-themed keywords have been published already since 1961, an increase in intensity is seen since the early 2000s. Similar increase tendencies are seen for keywords related to "renewable" (combined analysis of renewable energies, renewable energy, renewable energy resources, renewable energy source), "biomass", and "micro-CHP" (combined analysis of micro cogeneration, micro-CHP). However, the highest increase in total in the last decade is seen for the use of keywords related to "efficiency" (combined analysis of efficiency, energy conservation, energy efficiency, energy utilization, exergy, optimization). When considering these dynamics and the publishing tendency identified in Figure 2 (i.e., a higher proportion of journal articles than conference proceedings in the latest wave of research), it can be concluded that more profound and intense research is currently being published on various aspects of Stirling engine use. This includes not only technical and experimental papers but also an increased consideration of opportunities for the transition to renewable sources and the transformation of energy resources more efficiently.

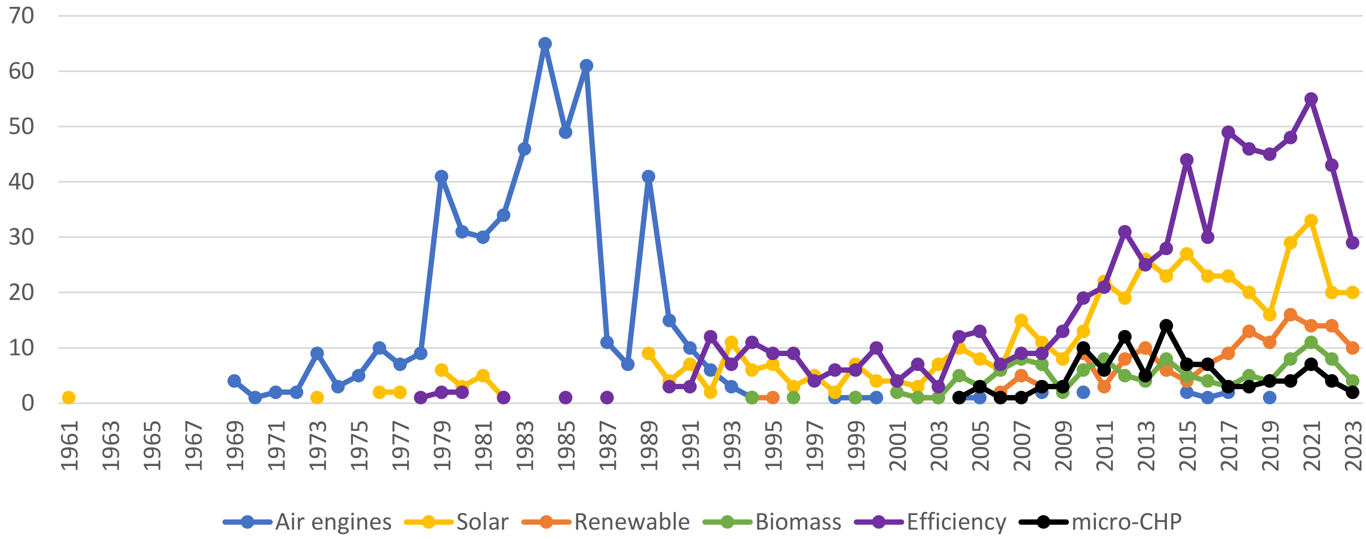


**Figure 3.** Dynamics of other topical keywords that are used in publications mentioning the keyword "Stirling engine" (data source: Scopus database).

**Table 2.** Summary of the quantitative results for all three research questions (data source: Scopus database).

| RQ | Retrieved Records | Retrieved Full Papers | Time Series Range | Document Type in Selection |
|---|---|---|---|---|
| RQ1 | 3997 | n/a | 1960–2023 | 1978 articles, 1948 conference papers, 71 review |
| RQ2 | 41 | 34 | 2001–2022 | 24 * articles, 15 conference papers, 1 review |
| RQ3 | 8 | 8 | 2009–2017 | 5 articles, 2 conference papers, 1 review |

* The query returns 41 records; however, it was manually identified that publication [36] has two duplicate records in Scopus, and therefore, duplicates were removed from further analysis.

Regarding the geographic coverage of the analyzed publications, Figure 4 summarizes the countries that most frequently publish Stirling engine-related studies. Among the 3997 documents evaluated, the country is not specified clearly for 1057 documents. For the remaining documents, 629 publications originated from the United States of America, followed by China (424) and Japan (178). Other countries included Iran (172), France (157), the United Kingdom (140), Italy (134), Germany (112), Canada (104), India (91), and Turkey (86) (see Figure 4). It must be noted that European Union countries in total have published 838 documents mentioning Stirling engines, which, combined, is higher than the USA.

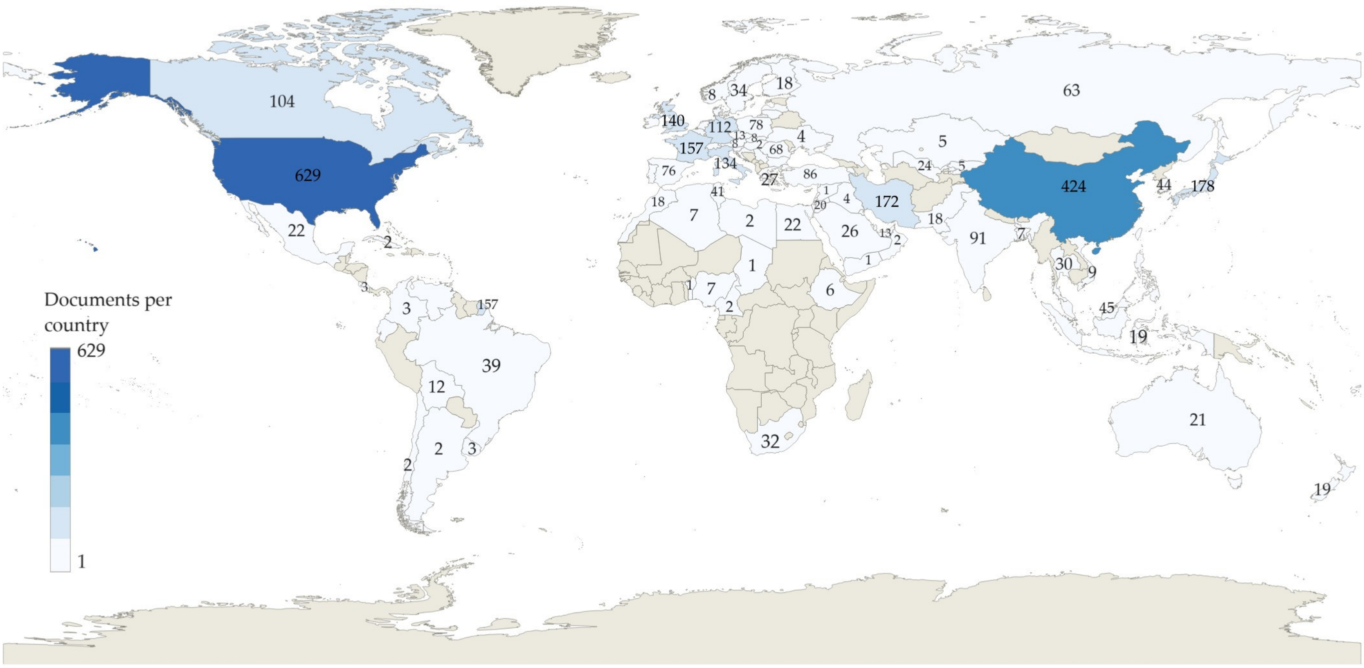


**Figure 4.** Geographical distribution of publications mentioning "Stirling engine" (data source: Scopus database; visualisation by authors (QGIS software, version 3.34.1.)).

Considering institutional affiliation, 160 different institutions were represented in the sample. Most publications originated from the NASA Glenn Research Center (124) located in the United States, followed by the Chinese Academy of Sciences (101), University of Calgary in Canada (81), Technical Institute of Physics and Chemistry Chinese Academy of Sciences (64), the University of Chinese Academy of Sciences (64), Mechanical Technology, Inc. in Latham, NY, the United States (58), Gazi University in Turkey (56), National Cheng Kung University in Taiwan (48), Sunpower Inc. in Athens, OH, the United States (42), Huazhong University of Science and Technology in China (38). It must be considered that the range of 60 years is assessed, but publishing in internationally indexed databases has peaked in the two recent decades due to global digitalization.

The international collaboration among authors in this field can be visualized using bibliometric data analysis programs, for example, VOS viewer (version 1.6.19.) [37]. Figure 5 shows the linkages between countries that have co-authored papers with node weights based on the number of documents and normalization by association strength. The USA is leading in collaborations and has co-published mostly with China and Japan, which are also the next two countries with the most co-published articles as indicated by the size of nodes.

VOS viewer visualization possibilities are also used to analyze the timely dynamics of keywords used in the retrieved articles. Figure 6 presents the overlay visualization of co-citations of all keywords (both author keywords and indexed keywords). The color scale is based on the average time of publication of the documents including a particular keyword, thus, it is possible to indicate which keywords are used more often most recently. The minimum number of keyword mentions was set to 50 to acquire a representable set of keyword clusters, and close duplicates were combined by providing a replacement thesaurus. Hence, 84 keywords were mentioned in at least 50 publications and they combine into three main clusters. These results provide another way to visualize the aforementioned conclusions that "air-engines", as well as "heat engines", "heat exchangers", and other thermodynamic keywords were much more popular before the 2000s. Energy efficiency, micro-CHP, biomass, renewable energies, waste heat utilization, computation fluid dynamics are keywords with the most recent average publication years.

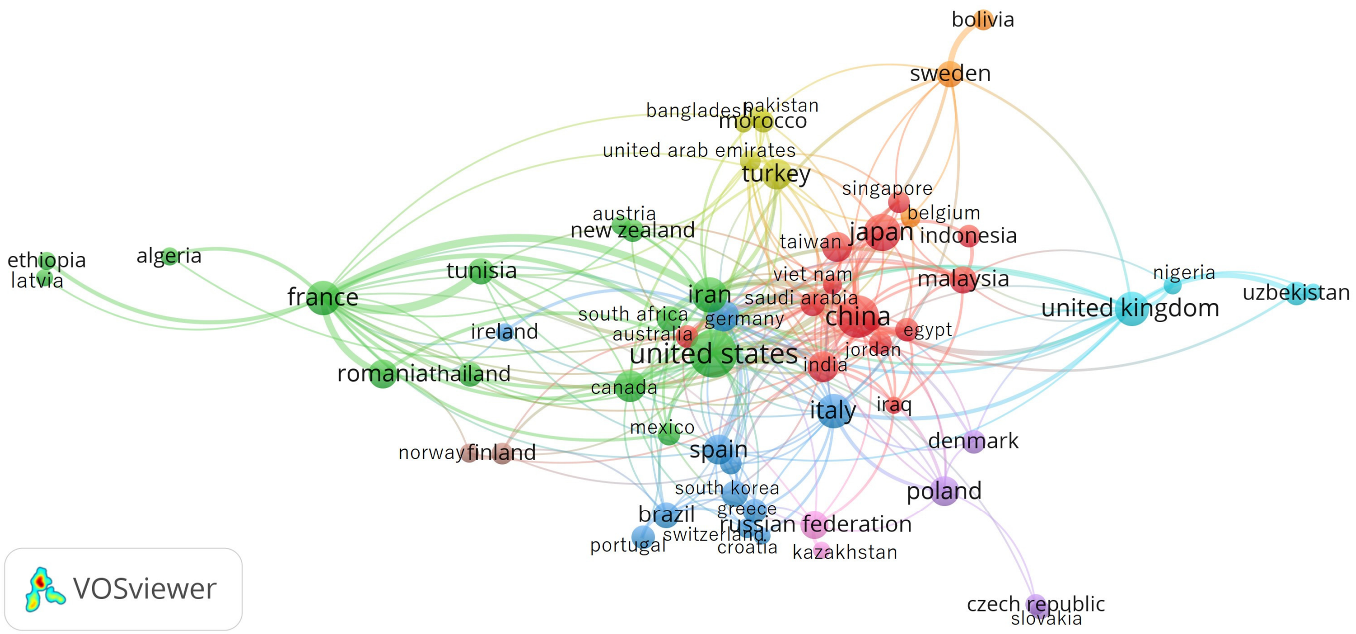


**Figure 5.** Network visualization of the most common countries in RQ1 sample (node weights based on document number, normalization by association strength, various colors represent different collaboration clusters) (data source: Scopus database, visualisation: VOS viewer software, version 1.6.19).

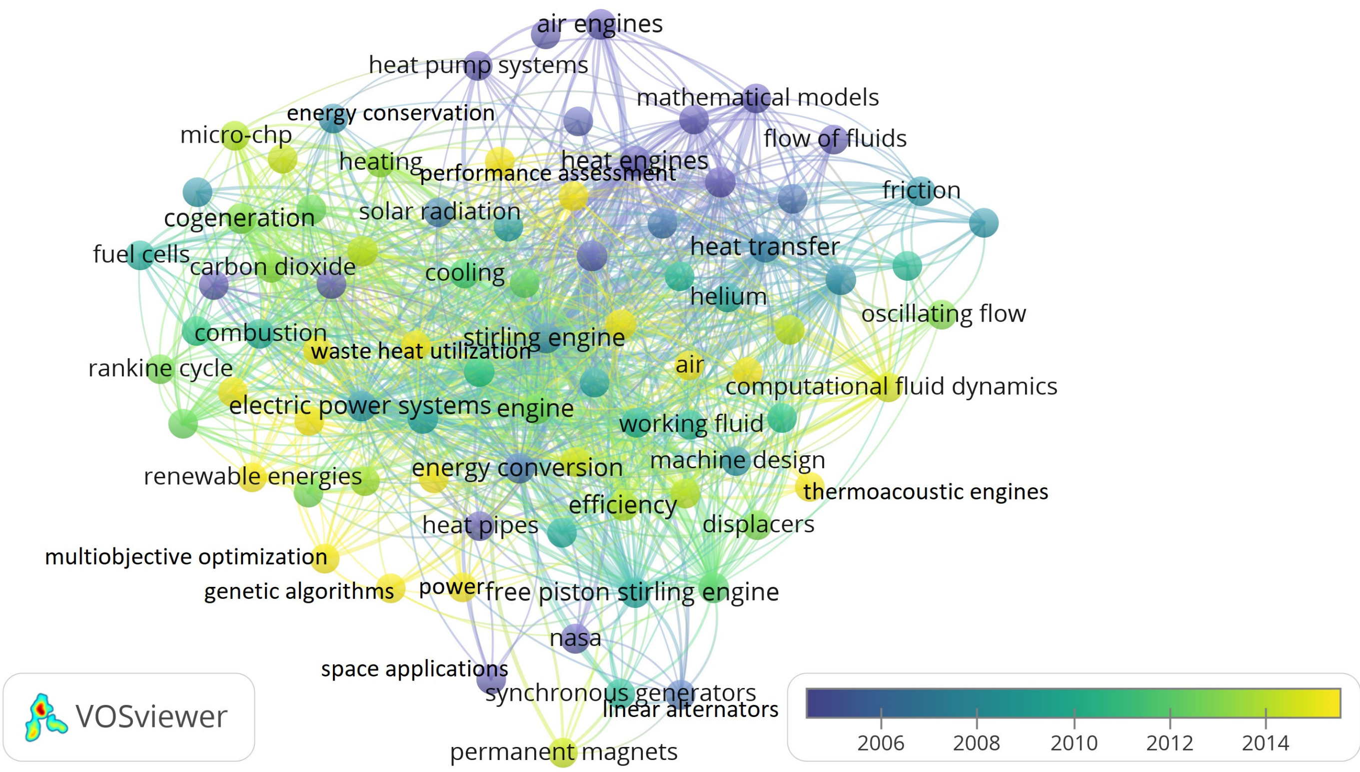


**Figure 6.** Overlay visualization of the most common keywords in RQ1 sample (publication year-based color scale, node weights based on occurrences, scores based on average publication year) (data source: Scopus database, visualisation: VOS viewer software, version 1.6.19).

In order to answer RQ2, another iteration of document retrieval based on a dedicated set of search criteria (see Table 1) was performed. The aim was to select the particular set or Stirling engine-related literature that also addresses residential-level applications and biomass as a fuel. The research string used for RQ1 was supplemented by the keywords "residential" and "household", which separately returned 164 and 42 articles, accordingly; and in a combination through logical OR resulted in 194 articles. To achieve an even better coverage of household-scale technologies, the six most popular variations of micro cogeneration-related keywords were obtained from RQ1 keyword statistics and added to the research string with the logical OR function. This query returned 325 articles, but the set was subsequently reduced by adding the keyword "biomass" to this string through logical AND function. The summary query returned 41 scientific publications (reduced to 40 documents after duplicate removal, for the detailed list or retrieved records see Table S1) that are further analyzed in this section and content analyzed in Section 3.2.

Hereafter, the statistics of publications selected to answer RQ2 are summarized. The earliest of the retrieved publications have been published in 2001; however, 95% of the publications on this topic have been published between 2010 and 2023. An increase is seen in the years 2014, 2015 (with 4 publications annually) and 2021, 2022 (with 5 publications annually). In the selected set, 24 publications were journal articles, 15 conference papers, and 1 review. A total of 110 researchers have been involved in publishing 40 documents which correspond to RQ2. Regarding geographic coverage, the highest number of publications in this sample were from Romania (7), France (5), Italy (5). Altogether, 36 documents were connected to authors from Europe, for Asia—7, for South America 4, for Middle East—3, and for Australia—2. This shows the particular importance and topicality of this subject in Europe. Articles are mostly published by researchers or groups of researchers from a particular country, but collaboration between countries is seen between Italy and UK [38,39], and by particular international researchers of Sweden and Bolivia [36,40], Australia, Iran, and Malaysia [41,42].

As evident from a quantitative analysis, this research sub-direction has developed lately (in the last 20 years), with a slowly increasing tendency. The geographic distribution of the acquired sample indicates that in Europe, this subject is quite topical to the scientific community. It is likely that the EU's purposeful strive to increase the use of renewable energy resources has encouraged this research. European Commission, Interreg, and Horizon 2020 project funding are the most frequently cited funding sources for these studies, but the Commission for Environmental Cooperation (founded by the Governments of Canada, Mexico, and the United States [43]), the Engineering and Physical Sciences Research Council (UK), and the European Bank for Reconstruction and Development are also named.

In addition to environmental and climate change concerns, the current and future energy security challenges will also further encourage Stirling engine research. Therefore, RQ3 is dedicated to the implications of the Stirling engine within the fields of energy supply, energy security, and environmental research. The dedicated search string returned 8 documents that have been published between 2009 and 2017. On the one hand, it is a very small set of documents, but on the other—it indicates the recent topicality of the subject. The retrieved articles in this set are from Italy, UK, Bulgaria, Canada, India, Pakistan, Romania, and Turkey. In contrast to documents in RQ1 and RQ2, no overall research trend conclusions can be derived due to too few responses.

### 3.2. Qualitative Analysis—Tendencies of Stirling Engine Biomass Co-Generation Use

In this section, we contrast various aspects of Stirling engines in context of sustainability and energy security. We analyze the promising research tendencies regarding Stirling engine use, considering microgeneration (household or individual users).

Firstly, the abstracts of all retrieved records ($n$ = 40) were analyzed, and the studies were classified as experimental studies ($n$ = 19), simulation and modelling ($n$ = 12), or other ($n$ = 9), which included conceptual analyses and reviews. According to the considered research subject, the studies were classified as those concerning mainly technical improvements of Stirling engine biomass-fueled CHP systems ($n$ = 23), those analyzing multiple renewable source integration or wider energy systems (rural, village) ($n$ = 7), summary papers as reviews ($n$ = 6), and other ($n$ = 4), i.e., conceptual or policy development studies.

Typically, the main research direction in studies retrieved based on the dedicated search string for RQ2 is concerned with the experimental investigation of the technical improvement opportunities of Stirling engine and CHP integrated systems [44–47] or comparison of experimental and simulation data [48,49]. The clustering of the retrieved documents allowed the authors to identify a research sub-direction on Stirling engine and fluidized bed combustor integration [45,50]. Researchers report on experimental set-ups of 40 $kW_{th}$/0.5 $kW_e$ [51], 0.5 $kW_e$ [52].

For environmental sustainability, the main advantages of the Stirling engine include high thermal efficiency, noiseless running, and a low pollution index [13]. As the Stirling engine historical development trend identified (see Section 2), the topicality and popularity of the technology have fluctuated throughout the years. However, in recent years, and also with more widespread opportunities for publishing, research intensity is increasing. One of the promising recent development directions identified through the content analysis of the papers selected by the structured literature analysis approach is research regarding biomass-fueled technology and Stirling engine integration. The biomass-fueled Stirling engines have been designed and/or tested with several energy resources—pellets [36,52–54], wood powder [55], energy produced from poultry litter co-combustion [56]. Authors report that other biomass, as diverse as bagasse, sawdust, wood logs, pruned orchards, wheat straw, switch grass, and poplar, can be used to produce the required heat for Stirling engines [13,57].

Some studies are of a particularly regional perspective, i.e., [58] design wood biomass regionally sufficient system for a village in Hungary, while [59] investigate a case study at the household level for conditions in South-East Romania. Huang et al. [60] provide a simulation and modelling of a Stirling engine and biomass trigeneration system for a case study building in Northern Ireland.

As indicated during the preliminary research and keyword analysis, Stirling engine use in combination with micro-CHP is an emerging technology that is especially interesting for decentralized generation. The application of renewable energy sources in micro-CHP and Stirling engine systems is increasingly topical; however, there are still practical challenges. Source intermittency is a significant factor when using solar or wind, while biomass is considered a more stable source [61,62]. Ferreira et al. [63] developed and solved a numerical model to compare biomass and solar energy as a heat source for the Stirling engine. In their results, the biomass-fueled version achieved higher electricity output and efficiency than the solar-powered system [63]. Cardozo and Malmquist [40] compared the performance of the Stirling engine with wood and sugar cane bagasse pellets, and while efficiency was lower with wood pellets, the CHP efficiency with bagasse pellets was over 83%. Ranieri et al. [64] note commercial Stirling engines have reduced efficiencies in comparison to ideal cycles. Chmielewski et al. [9] investigate Stirling engine micro co-generation as a potential technology for households using solid fuels for heating in Poland on a laboratory scale. Parashchiv et al. [65] suggest a biomass-based Stirling engine in combination with PV panels for a trigeneration application. In another proposed cooling, heating, and power small-scale biomass combustion-based plant, Maraver et al. [66] note that the main drawback for considering Stirling engines is their low market availability. In addition, the low-temperature Organic Rankine cycle outperforms Stirling engines in terms of investment costs, operations, and maintenance issues (due to higher heat source temperatures required for a Stirling engine and potential biomass ash issues) [66].

For off-grid RES systems, a significant challenge can be production–demand management [67]. Also, excess or surplus energy generation is a crucial challenge [68]. While biomass-based micro-CHP can provide generation stability to a larger degree and is more controllable than other renewables (as PV and wind power) in terms of production intermittency, the main challenges are related to the lack of significant heat demand in the summer, which leads to reduced overall efficiency of the system. Specifically for Stirling engine use, Staffel et al. [69] note that, due to a high heat-to-power ratio and dependence on heat demand, Striling engines can only run intermittently during the summer, while Ortwein and Lenz [70] emphasize that constant power output is also a limitation as the technologies are less flexible. When analyzing the impact of micro-generation on local sustainability, Brandoni et al. [15] stress the importance of planning and management to achieve $CO_2$ reduction, increase grid stability, and increase renewables' share. Alanne and Jokisalo [71] investigate a system integrated with a chargeable electric car as the power consumer during nighttime. A topical question for technology choice is the sizing. Chmielewski et al. [9] suggest that micro-cogeneration is the most appropriate to use in private companies, small factories, and households. Kramens et al. [44] also note that Stirling engines are more suitable for larger dwellings; hence, their application and efficiency at the single house level still have to be assessed in detail.

Another upcoming trend is the application of integrated systems of PV and Stirling engine hybrid cogeneration. Aunon-Hidalgo et al. [12] report on a combined PV-solar thermal collector and micro-CHP Stirling engine system as an attempt to achieve a reliable, autonomous, self-sufficient integrated system for households [12]. İncili et al. [16] analyze empirical data from a system of PV assisted fossil (lignite coal) fueled boiler with a Stirling engine. In their case study, the economic analysis indicated that the combined use of PV and Stirling engine is more feasible than only Stirling engine because the investment costs per kWh were 40% lower for combined use [16]. The simulation-based analysis by Balcombe et al. [72] shows that a Stirling engine and CHP system aids household self-sufficiency more than PV because more of the generated power is consumed instantaneously.

Regarding RQ3, though the gathered set that fits the query is small, most of the articles indicate that Stirling engine technology directly aids energy security by diversifying electrical energy production [73]. Aliabadi et al. [8] state that energy security and climate change concerns are at the base of co-generation interest increase. Brandoni et al. [15] emphasize the ability of micro-CHP energy systems to increase energy security, achieve climate targets, and move towards sustainable development. Incili et al. [16] mention the micro-CHP advantages to provide more energy security when they propose a fossil-based (coal), micro-CHP Stirling engine, and PV system. Elmer et al. [74] consider energy security when analyzing the advantages of fuel cells and comparing them to traditional combustion-based systems, such as the Stirling engine. Mazhar et al. [75], as well as Khadse and Khadse [76], only mention energy security as the advantage of Stirling engines but do not provide a more profound analysis. Overall, these studies acknowledge the advantages that cogeneration in general and Stirling engine use in particular provides for energy source and production, e.g., diversification and decentralization of energy production, but no in-depth analysis has yet been done on this sub-direction.

## 4. Discussion and Conclusions

The answer to RQ1, which was stated as "How has the Stirling engine literature developed over time?" was investigated by analyzing the statistics of the sample of documents retrieved according to the prescribed research protocol. It was identified that, for more than six decades, articles mentioning Stirling engines have been published in internationally indexed journals and conferences. The keyword dynamics showed that, initially, direct keywords such as heat engine, air engine, and thermodynamics were most frequently used in Stirling engine themed articles. However, in the last two decades, the publications have evolved to include much wider sub-directions, including themes that are very topical in the context of the Green Deal and renewable energy resources, i.e., solar energy and biomass technologies, increased energy transformation efficiency, and the use of micro-CHP technologies. Research on Stirling engine technologies is evolving, and nowadays, an increased number of scientists are publishing new studies with the aim of finding a feasible application for this technology in modern conditions.

The defined RQ2 was "What is the focus and latest tendencies in small-scale (residential) renewable energy-based Stirling engine research, with a particular focus on biomass?" The quantitative bibliographic and qualitative content analysis results corroborate the progress towards the use of renewable resources where solar-based power generation systems have already been widely covered by scientists for many decades, but also, the number of research articles related to biomass-based Stirling engines is increasing lately. Moreover, for the household or residential level, the use of hybrid systems, including micro-CHP, PV, and Stirling engine combinations, is increasingly investigated, indicating this as a future trend. Energy efficiency increase is also a topical question because the keyword and overlay analysis showed more frequent publishing in RQ1 and RQ2. For the energy security and independence aspects of Stirling engine applications, more profound research is needed, as there is a general lack of research on this topic and most existing articles only mention these as potential benefits but do not substantiate the assumptions.

With the aim to identify the current state-of-the-art and the topical development directions for Stirling engines in households, this research uncovers that, although Stirling engines may be associated as a mature method, the current transition to renewable energy resources keeps the research evolving. The necessity for decentralized small-scale heat and power solutions and for adaptation to climate change effects, i.e., grid disturbances due to extreme weather events, renews interest in Stirling engine applications for sustainability and energy security. This structured literature review provides an analysis of the specific research niche (RQ2) concerning Stirling engine use in small-scale (household) applications and in integrated renewable systems, and identifies the topic of the effects Stirling engine use has on energy security or energy independence (RQ3) as an interesting research niche for further studies. The limitations of the presented research are related to the selection of applied keywords (which was managed by comprehensive keyword identification and clear explanation of the reasons for keyword selection), the availability of full texts for retrieved records (higher availability of journal articles than conference papers), and the continuous development of the set of publications (which was managed by indicating the specific time when the research was carried out).

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17020383/s1, Table S1: List of articles retrieved based on RQ2 query; Table S2: List of articles retrieved based on RQ3 query. References [77–94] are cited in the supplementary materials.

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