*Inzinerine Ekonomika-Engineering Economics*, 2024, 35(1), 4–24

# The Development and Progress of Engineering Economics: A Retrospect and Prospect Based on Visual Analysis

**Yu Qian, Xunjie Gou, Zeshui Xu**

*Business School, Sichuan University*
*29 Jiuyanqiao Wangjiang Road, Chengdu 610064, China*
*E-mail: yuqian_echo@163.com; gou_xunjie@163.com; xuzeshui@263.net*

https://doi.org/10.5755/j01.ee.35.1.32448

*Engineering economics is a cross subject with a wide range of applications, and it has taken on different characteristics with the changing times. The aim of this paper is to depict a sufficiently elaborate and vivid knowledge map of this field, with further discussion and outlook on the hotspots presented therein. Based on the principles and methods of bibliometrics, we use several visualization tools, mainly Vosviewer, to present the characteristics of the published literature within the field of engineering economics from multiple perspectives. Specifically, we collect 624 engineering economics documents published in the Web of Science core collection database between 1915 and 2021, and quantitatively analyze them in the following three aspects: (1) basic data characteristics, including annual publications, annual citations, research directions, and highly cited publications; (2) outstanding performers and cooperations in the four levels of country/region, institution, source and author, including co-authorship, bibliographic coupling, co-citation and co-occurrence analyses; and (3) keyword analyses, including co-occurrence analyses, burst detection analyses, and high-frequency word clouds. In addition, we further explore important topics within the field represented by intelligent and green transformation.*

Keywords: *Engineering Economics; Bibliometric Analysis; Software Engineering; Artificial Intelligence; Environment.*

## Introduction

Engineering Economics (EE) is an important interdisciplinary subject that grows up on the basis of two long-standing fields, engineering and economics. Economics explains how to make rational distribution of limited resources to meet demands (Boehm, 1984; Backhouse & Medema, 2009). While the resources available for deployment can be used for achieving a variety of purposes, wealth creation is the one that receives relatively the widest attention. Generally speaking, economics can be divided into two main branches of microeconomics and macroeconomics, depending on the different research objects. The former one deals with the effects of decisions-making at the national or global level, while the latter one involves the decision-making at the individuals or organizations level (Boehm, 1984). As for engineering, it is an applied discipline that aims to use the knowledge of mathematics, physics and other natural sciences to develop devices that can benefit mankind (Afolalu *et al*., 2021). The theoretical studies and practical applications of engineering cover every aspect of daily life, including civil construction, machinery, energy, materials, traffic safety and agriculture. Systematic engineering thinking is essential for solving complex practical problems.

The management and completion of any project depends heavily on a series of decisions dominated by engineers. Whether the immediate purpose of the decision in question is to save time by adjusting the schedule or to improve quality by replacing materials or equipment, obtaining greater economic efficiency is always one of the primary end goals. Meanwhile, economists have also long been aware of the engineering nature of economics. Although scholars in the field have devoted themselves to the construction of theoretical models due to the rigorous social science attribute of economics, they have realized that the research in economics should not focus solely on academic discussions, but also on solving problems in real-life situations (Duarte & Giraud, 2020a). Correspondingly, engineering is concerned with the combination of theory and practice, that is, adopting the most appropriate compound methodology including scientific knowledge and accumulated experience to accomplish the best practice relying on the actual situation (Su & Colander, 2021). Thus, engineering provides effective tools for better integrating the principles and policies of economics into the socio-economic environment, while economics helps to clarify and realize the pursuit of profit in engineering practice (Duarte & Giraud, 2020a).

Naturally, the complementary relationship between engineering and economics has driven the emergence and development of EE. It can be defined as a comprehensive discipline that applies economic principles and mathematical skills for the analysis and selection of alternatives while relying on advanced technologies that meet performance criteria to allocate scarce resources to form the end result of achieving the expected economic goals and other requirements (Sullivan, 1991; Afolalu *et al*., 2021). There are many important time nodes in the early stages of the development of EE, and we organize 7 of them into the timeline in Figure 1.

However, the development of any intersecting subject is bound to proceed under constant questioning and inquiry about its necessity and innovativeness, accompanied by debates aimed at clarifying the concept and meaning of the field. In the case of EE, the identification of the ways in which engineering and economics interact helps to capture the theoretical as well as the practical significance of the field. A series of studies have put forward important insights on this issue, which provides us with valuable opportunities to further understand the connotation of EE. Duarte and Giraud (2020b) proposed two paradigms for the economics–engineering nexus, "economics as engineering" and "economics and engineering". Mariotti (2021a) then redefined the meaning of "as/and" and added the new paradigm, "economics for engineering", while Mariotti (2021b) explained the exploration of finding and forming these three paradigms. Hébert (2021) commented on Mariotti's work, pointing out that his research on the economics-engineering nexus is both insightful and promising, but there were also tricky problems to be solved. Mariotti (2022a) continues the debate with a further response and argues that economics and engineering are gradually coming to "a fruitful knowledge collaboration". Moreover, given that the intertwining of the two fields has entered a phase of diminishing returns, Mariotti (2022b) urged "the establishment of a new 'pluralistic alliance' between the different semi-autonomous branches of the two disciplines" to respond more effectively to increasingly complex realities.

This debate may not reach a fully recognized outcome, but the confrontations similar to it are key for building a more robust intellectual framework for EE and clarifying the developmental tasks specific to this interdisciplinary field. The corresponding studies sort through the interaction history between engineering and forge three vital paradigms for economics-engineering nexus, which makes them the critical reference information for defining the subject orientation of EE. As the basic components of EE, engineering and economics can enrich this crossing field by providing constantly updated theories, methods and tools. EE, however, cannot be satisfied with just being a vessel that simply holds engineering and economics. It still needs to complete the integration of knowledge between different disciplines and create new things that help to solve practical issues, which would in turn have a positive impact on advancing economics and engineering. The practical operation is much more difficult than purely conceiving, especially when the surrounding context is always dynamically changing.

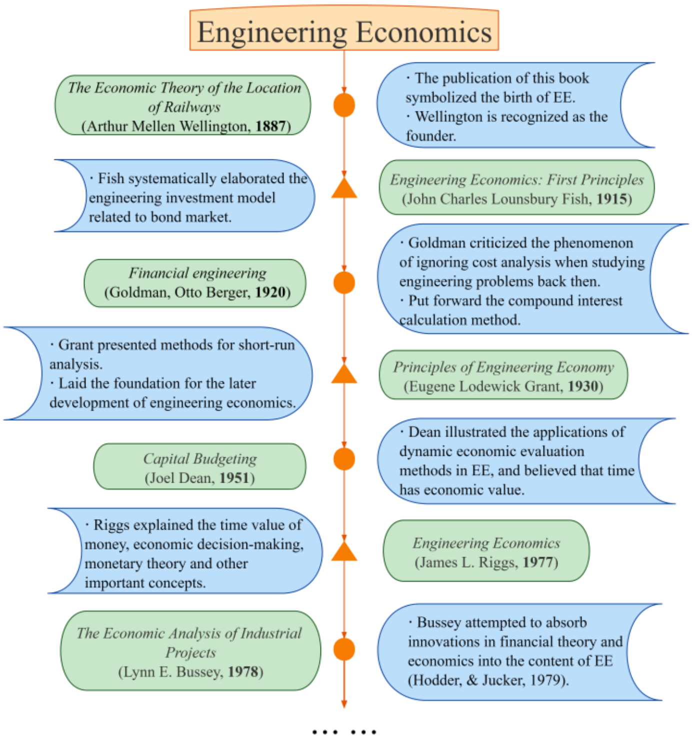


**Figure 1.** The Early Development of EE

Nonetheless, with the vigorous development of technology and social economy, the theoretical and practical research on EE has accumulated plenty of promising results. Various classical theories and techniques proposed and developed around EE are widely used in many fields. For instance, cash flow is one of the key calculation objects for EE analysis in project management, and the related concepts, such as TVM (Time Value of Money), PV (Present Value), FV (Future Value), breakeven points, are usually considered together (Su & Lucko, 2015). Moreover, the optimization design involved in system development is also a common controlling method in EE for minimizing costs while maximizing economic benefits, which may require the assistance of sensitivity analysis, decision tree and cost-benefit analysis to play the best results (Khlebnikova *et al.*, 2021). The new era brings new opportunities as well as new challenges. With the advent of the digital age, the new problems posed by increasingly complex artificial intelligence (AI) and other advanced technologies may exceed the processing scope of traditional methods (Hébert, 2021). Also, the global transition towards sustainable development has led to the emergence of more and more compound problems in EE, which usually involve multiple dimensions at the same time, such as environmental, economic and social. The rapidly changing external situation may be the fertile ground for broadening the intellectual landscape of EE, but it may also be an obstacle to clarifying the development trajectory and mission of the field.

Therefore, this paper intends to draw support from techniques of bibliometrics to sort out the work of EE so far and display the relevant analysis results through visualization tools, so as to grasp the research hotspots, cutting-edge technologies and development trends in the field. In general, there are three motivations for this bibliometric review. Firstly, the debate on the relationship between engineering and economics is still inconclusive, which means that the construction of subject knowledge in EE is not yet perfect. We need to keep abreast of dynamics in the field to track and find clues that are able to promote the development of EE. However, as this paper aims to provide a systematic review of EE based on a large body of relevant literature, its focus is on observing the prominent phenomena in existing academic research at a relatively macro level to reveal the main features of the field. Addressing specific issues, such as the mining and determination of the economics-engineering nexus paradigm, still requires deeper investigations in other forms that are more targeted, so it is not the purpose of the analysis in this paper. Secondly, the world today is facing a number of major reforms, and initiatives and actions represented by digitalization and sustainability transformation are having profound impacts on the growth of EE. A comprehensive and timely review of the research findings in the field would help us to capture the latest hotspots and anticipate promising future directions. Lastly, despite the long history of EE, there has been relatively few analyses and reviews based on its publications, let alone bibliometric reviews. In this paper, we would like to make an attempt in this very direction and add insights into the development of EE from this perspective to offer reference for future research.

Specifically, the main innovations and contributions of this paper lie in the following aspects: (1) Grasping the basic statistical characteristics and changes of documents in the EE field and exploring the key research results of different objects from multiple levels, including the total amount of literature, citation distribution, cooperative relationship, co-occurrence analysis, and emergence analysis. (2) Recognizing the authors, institutions, sources, and countries/regions who have made remarkable contributions in the field and displaying the corresponding academic hotspots and trends. (3) Discussing four key themes in the existing studies and pointing out the promising directions and practical issues that require sustained attention and in-depth further research.

The remaining parts of this paper are organized as follows: Section 2 briefly introduces the background of bibliometrics, the source of the data used for analysis, the functions of the visualization tools involved, and the overall research framework in this study. Section 3 is divided into three subsections which carry out bibliometric analysis and information interpretation of the general characteristics, the multi-form cooperation relationship in different research levels, and keywords, respectively. In Section 4, the four hot topics within existing research are discussed, and the future research directions and accompanying challenges are brought out, too. Finally, we give the conclusion and implications from this research in Section 5.

## Data and Methodology

In order to swiftly get a clear understanding of the intellectual landscape formed by documents in the field, we utilize the bibliometrics methodology to support the entire analysis process. Bibliometrics analysis helps us to process massive bibliometric data systematically and logically (Xu *et al*., 2023). On the one hand, it is able to investigate the top performers in a specific field from different angles without losing a hold of the whole picture (Qian *et al*., 2023a). This methodology can shed light on the transforming tracks of researchers’ preferences, which is beneficial for us to effectively lock the emerging area (Donthu, *et al*., 2021a).

Nonetheless, there are also shortcomings in the bibliometric analysis, which leads to the following limitations of this paper: (1) This review conducts bibliometric analyses on the basis of the limited existing literature collected, and the corresponding results have only a relatively short timeliness for revealing the dynamics within the field of EE. (2) The relevance and accuracy of the data selected have a significant impact on the results of the bibliometric analyses, and data screening cannot eliminate all possible negative effects. (3) The corresponding qualitative analyses of these quantitative results are largely dependent on the researcher's perspective and possess definite subjectivity. We have tried to overcome these inherent defects as much as possible in our analyses and elaborations, but the conclusions obtained in this study should still be treated dialectically (Donthu *et al*., 2021b).

To conduct a comprehensive bibliometric analysis in this paper, we choose the world-leading online database, Web of Science (WoS), as the data source. WoS is known as the oldest citation resource that owns a mass of prestigious academic journals used for scientific research (Adriaanse & Rensleigh, 2013), covering a wide range of academic fields including natural sciences, engineering technology, biomedicine, social sciences, art, and humanities. Not to mention that it has a high degree of compatibility with most visualization software on the market.

Based on the determined analytical method and data source, we also need to select the keywords for data searching. For the purpose of this research, we hope to complete as comprehensive a picture of the development of the field as possible and to capture salient topics and contributors in existing studies. Limiting the search scope with subjective preference should then be avoided. As two fundamental components of EE, neither the types of engineering nor economics should be specified at the literature search stage, e.g., chemical engineering or industrial economics. Hence, it is more in line with the research purpose of this paper to conduct a search around only the two sets of keywords, “Engineering Economics” and “Engineering Economy”. The data obtained would be suitable for objectively presenting the popular applied theories and tools as well as the hot research directions with potential in the field. Over time, the concept of EE has been enriched and evolved through a lot of theoretical and practical studies. Gill (1943) considered that “engineering economics” refers to “the wise handling of finance in engineering projects.” Aydin *et al.* (2018) defined “engineering economics” as “the systematic evaluation of the economic merits of proposed solutions to engineering problems.” Similarly, DeGarmo *et al.* (1989) described “engineering economy” as a subset under engineering that uses techno-economic analysis to determine the optimal engineering course of action. From an educational perspective, Burns *et al.* (2020) agreed that the realization of EE is closely linked to both engineering and financial knowledge. Both of these two expressions are able to reflect the essence of EE as a cross-discipline and appear frequently as synonyms representing this field in related research.

Therefore, we collect data through the Web of Science Core Collection database by setting the search formula as follows: Topic = “Engineering Economics” or “Engineering Economy”; Timespan = 1900-2021. We add the results of the two retrievals to the marked list separately and remove documents that are weakly related to EE or even not belong to this field. Then, we choose the “Tab-delimited (Win)” format in the “other file formats” option to export the full information of all records including Author(s)/Editor(s), Title, Source, Abstract, Times Cited, etc. As of September 16, 2021, a total of 624 documents are selected as the objects of bibliometric and further analysis.

In this study, Vosviewer is selected as the main visualization tool for analyzing literature data. Specifically, we use it to complete co-authorship, bibliographic coupling, co-citation and co-occurrence analyses at different stages of the bibliometric analysis, which are able to reveal different types of key information in the form of various interconnected networks. In addition, we also perform several quantitative analyses using CiteSpace and the visualization capabilities that come with WoS. The burst detection analysis in CiteSpace helps to complement the perspective of analyses in terms of both temporal and intensity evaluation criteria. The results of simple analyses such as research direction, the number of annual publications and annual citations are available directly from WoS. The research strategy and framework are shown in Figure 2.

## Results Analysis

### *Overall Characteristics of Publications*

In this subsection, we briefly illustrate the basic characteristics of the 626 documents retrieved in WoS using graphs and tables to form a general impression of the EE field. Among those collected documents, there are 12 different types, including article (326, 52.08 %), proceedings paper (229, 36.58 %), book review (40, 6.39 %), review (25, 3.99 %), editorial material (16, 2.56 %) and others (22, 3.51 %), as shown in Figure 3. Apparently, article and proceedings paper account for the largest proportions while the remaining types account for a relatively small proportion. Due to the repeated counting of partial documents in multiple categories, the total number of documents exceeds 624, and the total percentage is not 1. If the same situation occurs in other analysis later, the reason is the same.

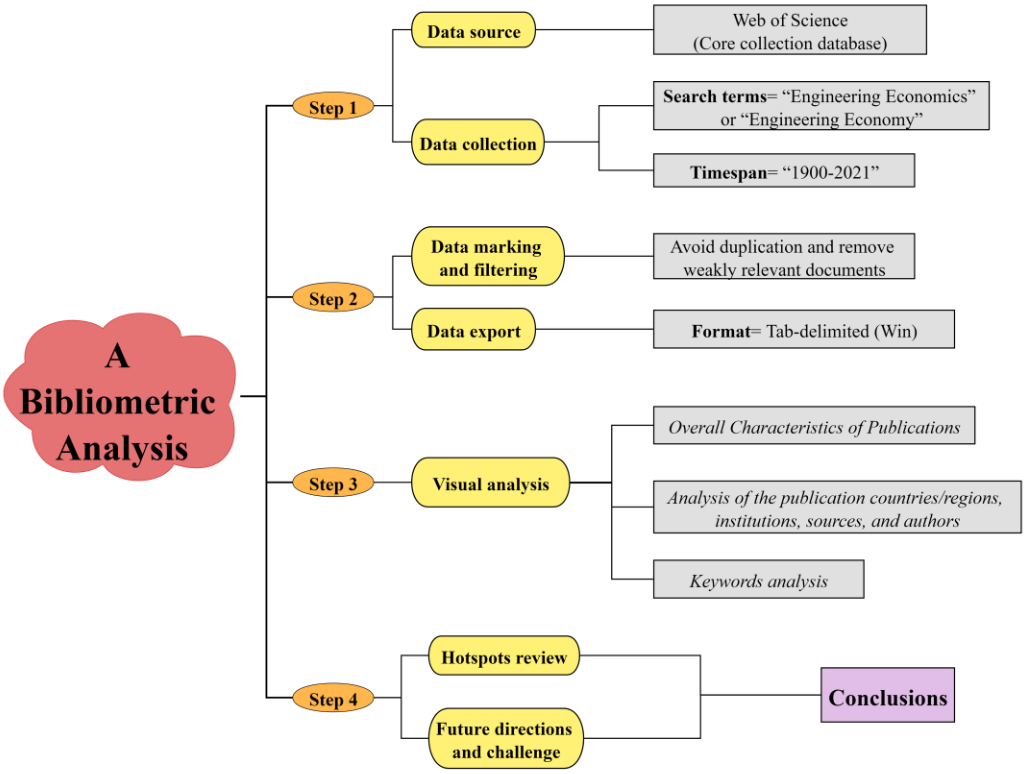


**Figure 2.** The Overall Framework of Methodology

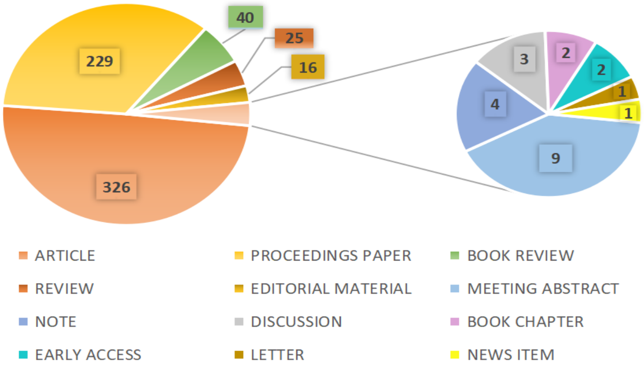


**Figure 3.** The Types of Existing Publications in EE

### *Yearly Trend of Publications*

Figure 4 and Figure 5 display the total number of annual publications and the total number of annual citations in EE, respectively. As we can see, the first document belongs to EE field in WoS, *Engineering Economics*, was published in November 1915 (Hess, 1915). However, it was not until around 2000 that the annual number of publications broke through double digits and began to grow steadily. As far as the WoS Core Collection database is concerned, although the annual number of publications on the topic of EE has shown an upward trend in recent years, the total number of publications in this field is still not large. Relatively speaking, the rising curve of annual citations is more obvious and steeper. Taken together, these two figures reflect that scholars maintain their focus on the dynamics and achievements within EE, but they still need to strengthen their efforts in the development of specific results of EE.

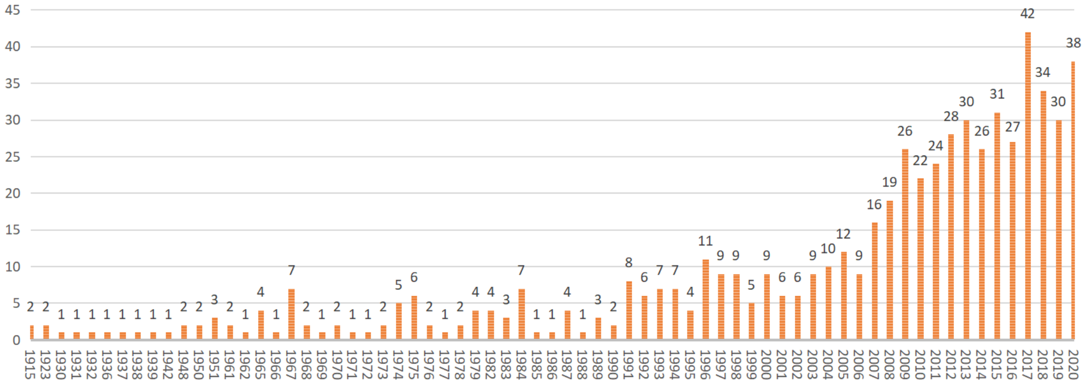


**Figure 4.** The Total Number of Annual Publications in EE

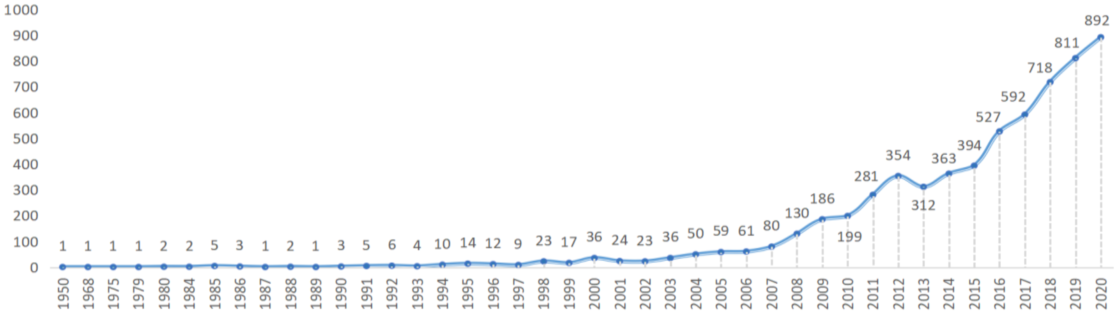


**Figure 5.** The Total Number of Annual Citations of Publications in EE

### *Research Directions*

By looking at the research directions covered in the accumulated EE literature over time, we could form an initial idea of the research priorities in the field. As far as the selected literature is concerned, there are 65 research directions are covered, and the top 15 ones are presented in Figure 6 (the areas on the figure are not strictly proportional to the values of each entry, but merely reflects the relative relationship between the entries.). We note that "ENGINEERING" (total number: 316, percentage: 50.48 %) occupies relatively the largest area. The field of engineering encompasses numerous types of practical applications, such as software engineering, systems engineering, environmental engineering, electrical engineering, mechanical engineering, etc. A large number of specific engineering projects serve as the basis on which the theoretical and practical results of EE can be accumulated continuously. Economics is another fundamental element for the existence, development and innovation of this field. Particularly, the theories and techniques related to "BUSINESS ECONOMICS" (100, 15.97 %) appear frequently within the scope considered. However, although the number of publications in engineering is more than that in economics in this relative range, it does not suggest that EE is based on a simple relational paradigm in which economics is an appendage of engineering, but only reflects to some extent the fact that viewing and presenting practical problems in an engineering format is a key step to find solutions by using EE-related techniques. "COMPUTER SCIENCE" (112, 17.89 %) accounts for a large proportion while "AUTOMATION CONTROL SYSTEMS" (18, 2.88 %) and "SCIENCE TECHNOLOGY OTHER TOPICS" (26, 4.31 %) also gaining some attention, reflecting the trend of digitization and intelligence in the development of EE in the information age. In addition, these two directions of "ENVIRONMENTAL SCIENCES ECOLOGY" (52, 8.31 %) and "ENERGY FUELS" (51, 8.15 %) also embody the consideration and balance of environmental and energy factors in EE-related research under the call for sustainable development.

**Figure 6.** Visualization Tree Map of Research Directions in EE Based on Existing Publications

### *Highly-Cited Publications*

Table 1 lists the top 10 documents based on the number of citations (NC) as well as their source, year and average annual number of citations, from which we attempt to acquire two aspects of information. On the one hand, this table reflects the most popular documents, and important journals worthy of continuous attention, which can be valuable references and sources of inspiration for future research. On the other hand, the documents here also reveal the hot topics for years now, and once again confirm that computer science and environmental science have received general attention.

Table 1

**The top 10 Most-Cited Publications in EE**

| Reference | Title | Year | Source | NC | NC/year |
|---|---|---|---|---|---|
| (Mellit & Kalogirou, 2008) | Artificial intelligence techniques for photovoltaic applications: a review | 2008 | Progress in Energy and Combustion Science | 433 | 30.93 |
| (Tsatsaronis, 1993) | Thermoeconomic analysis and optimization of energy-systems | 1993 | Progress in Energy and Combustion Science | 331 | 11.41 |
| (Boehm, 1984) | Software engineering economics | 1984 | IEEE Transactions on Software Engineering | 251 | 6.61 |
| (Mandavi *et al.*, 2015) | Metaheuristics in large-scale global continues optimization: a survey | 2015 | Information Sciences | 222 | 31.71 |
| (Mellit *et al.*, 2009) | Artificial intelligence techniques for sizing photovoltaic systems: a review | 2009 | Renewable and Sustainable Energy Reviews | 211 | 16.23 |
| (Khalilpour *et al.*, 2015) | Membrane-based carbon capture from flue gas: a review | 2015 | Journal of Cleaner Production | 167 | 23.86 |
| (Kliestik *et al.*, 2018) | Bankruptcy prevention: new effort to reflect on legal and social changes | 2018 | Science and Engineering Ethics | 163 | 40.75 |
| (Banga, 2008) | Optimization in computational systems biology | 2008 | BMC Systems Biology | 161 | 11.50 |
| (Young, *et al.*, 2000) | The waste reduction (WAR) algorithm: environmental impacts, energy consumption, and engineering economics | 2000 | Waste Management | 149 | 6.77 |
| (Michalski, 2000) | Learnable evolution model: evolutionary processes guided by machine learning | 2000 | Machine Learning | 146 | 6.64 |

### *Analysis of the Publication Countries/Regions, Institutions, Sources, and Authors*

In this subsection, we first divide the analysis objects into three levels, and then select appropriate analysis methods in accordance with the characteristics of each object to achieve the presentation of their performances on fundamental indicators and the visualization of the relationships between various items.

### *Country/Regions Level*

The distribution of documents on different countries/regions is clearly distinguished as shown in Figure 7, and Table 2 shows in detail the performance of the top 10 countries/regions in terms of the number of documents (ND), NC, NC/ND, initial year and the percentage of ND. Among the 10 most productive countries/regions, the advantages of the USA are obvious in all indicators. Not only did it start research in the field of EE much earlier than other countries/regions, but it also maintains a continuous high-quality output. Furthermore, it is worth noting that despite its relatively latest start in this field, Spain owns a conspicuous performance on NC and NC/ND, indicating that Spain is establishing its academic authority on steady pace in the field of EE. And the story is similar in Italy. China, however, with ranking second on the indicator ND, has not received high enough citations, which results in the lowest ranking on the indicator NC/ND.

Table 2

**The Top 10 Countries/Regions Based on ND in EE**

| R | Country/Region | ND | % | NC | NC/ND | Initial year |
|---|---|---|---|---|---|---|
| 1 | USA | 226 | 36.2 | 3103 | 13.730 | 1942 |
| 2 | China | 78 | 12.5 | 278 | 3.564 | 1991 |
| 3 | England | 31 | 4.9 | 492 | 15.871 | 1973 |
| 4 | Canada | 21 | 3.4 | 436 | 20.762 | 1994 |
| 5 | Germany | 21 | 3.4 | 500 | 23.810 | 1993 |
| 6 | Spain | 18 | 2.9 | 644 | 35.778 | 2003 |
| 7 | India | 17 | 2.7 | 130 | 7.647 | 1992 |
| 8 | Turkey | 16 | 2.5 | 318 | 19.875 | 2000 |
| 9 | Brazil | 14 | 2.2 | 152 | 10.857 | 1996 |
| 10 | Italy | 13 | 2.1 | 433 | 33.308 | 1995 |

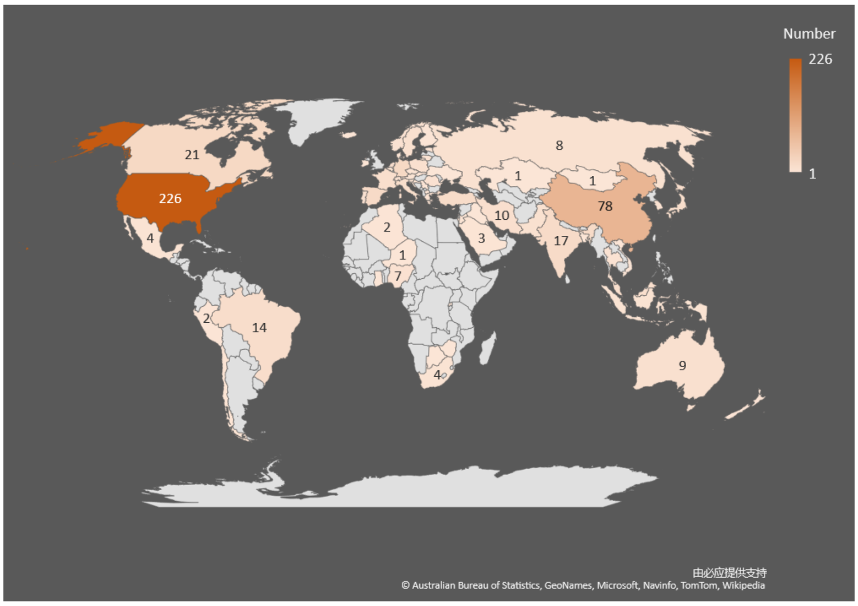
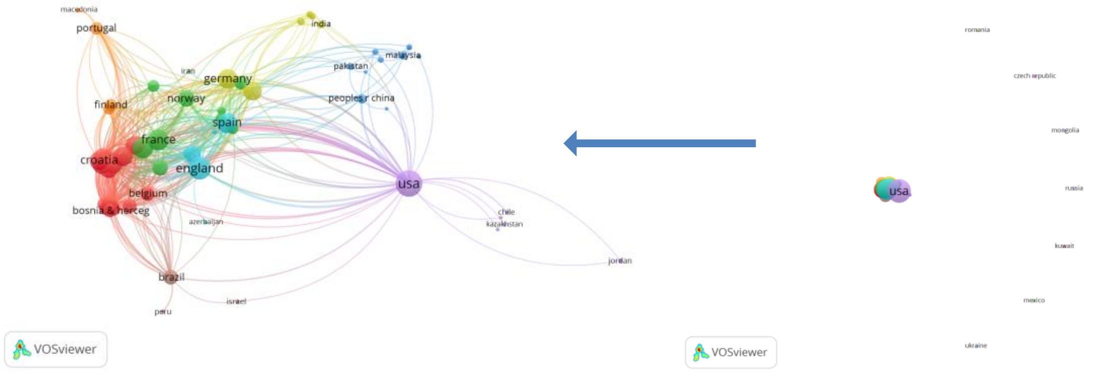


**Figure 7.** The Global Geographic Distribution of Publications in EE

With the help of the visualization tool, Vosviewer, we are able to have a concrete understanding of the cooperation relationships between countries/regions. In the collaboration network presented in Figure 8, the links represent the co-authorships between different countries/regions. We set the weights as total link strength (TLS), which means the more cooperation the country/region has with other countries/regions, the larger the node representing it. Since there is no cooperative behavior in seven countries/regions including Romania and Russia, the overview map in Figure 8 (a) appears to be sparse, so we zoom in and observe the largest sub-network in Figure 8 (b). Among the top 10 countries/regions that have the most cooperation with others, the USA (TLS: 94), England (73), France (62), Spain (57), Germany (51) and Croatia (48) are easy to find in the detail image while the remaining four countries of Scotland (59), Sweden (54), Italy (50) and Australia (47) are not shown because they are too close to other nodes. Obviously, at least half of the countries/regions in Table 2 also attach importance to collaborative research. Other than that, Scotland and Croatia, ranking 30th and 27th respectively based on the indicator ND, promote development in this field by increasing communication with other countries/regions wisely, which is actually an aspect that needs to be strengthened for China (13) and India (9), the 36th and 39th on the TLS list.



**(a)** **(b)**

**Figure 8.** The Countries/Regions Collaboration Network Based on TLS

### *Institution Level*

Likewise, we analyze the performances of more than 700 institutions in the field of EE. Owing to the fact that the results obtained by analyzing different indicators are quite different, we present three groups of top ten institutions respectively in Table 3 under 3 different ranking standards, i.e., ND, NC and TLS. The multiple institutions have dissimilar emphasis. Only the Carnegie Mellon University and IRCCS Mario Negri appear on lists of more than one indicator, which fully demonstrate their balanced development strategy in EE. Additionally, we notice that the top 2 most-cited institutions, Cyprus University of Technology and Universite de Jijel, have exactly the same citations, that's because they collaborated on the same two documents, *Artificial intelligence techniques for photovoltaic applications: a review* (Mellit & Kalogirou, 2008) and *Artificial intelligence techniques for sizing photovoltaic systems: a review* (Mellit *et al.*, 2009), with 428 and 210 citations, respectively. The latter document is also the reason why the 7th and 8th institutions are on the NC list. Although the average ND of these 10 highly-cited institutions is only 2.3, the high NCs of them already show their value and remind us to take relevant studies involving these institutions seriously as well as exploring the potentials within.

The United States holds 11 of the 28 institutions involved. Italy, Australia and Sweden own 2 institutions each, and the remaining institutions belong to Cyprus, Algeria, Iran, Canada, Malaysia, Spain, Austria, Slovenia, Poland, Estonia, Scotland and Netherlands. This situation once again demonstrates the absolute strength of the USA in the EE field, and we learn about more institutions to watch. As for the indicator TLS, we will explain it combing the results of bibliographic coupling between institutions.

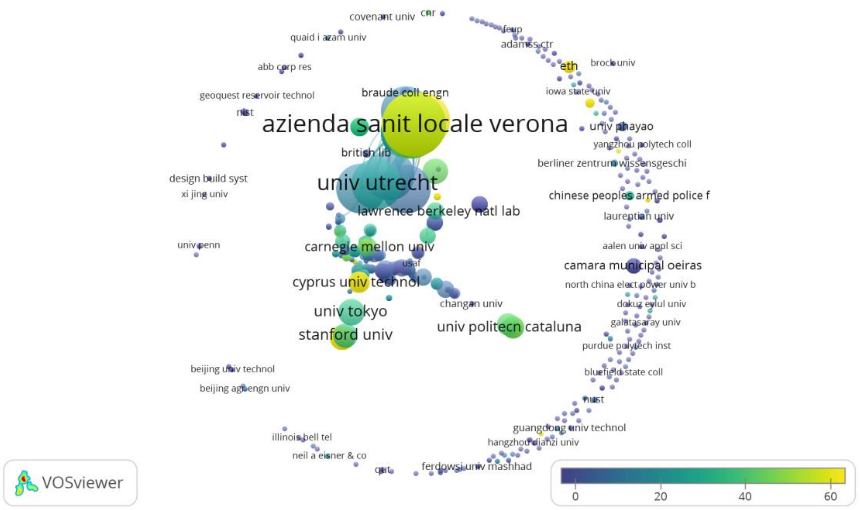
Table 3

**The Top 10 Institutions Based on ND/NC/TLS in EE**

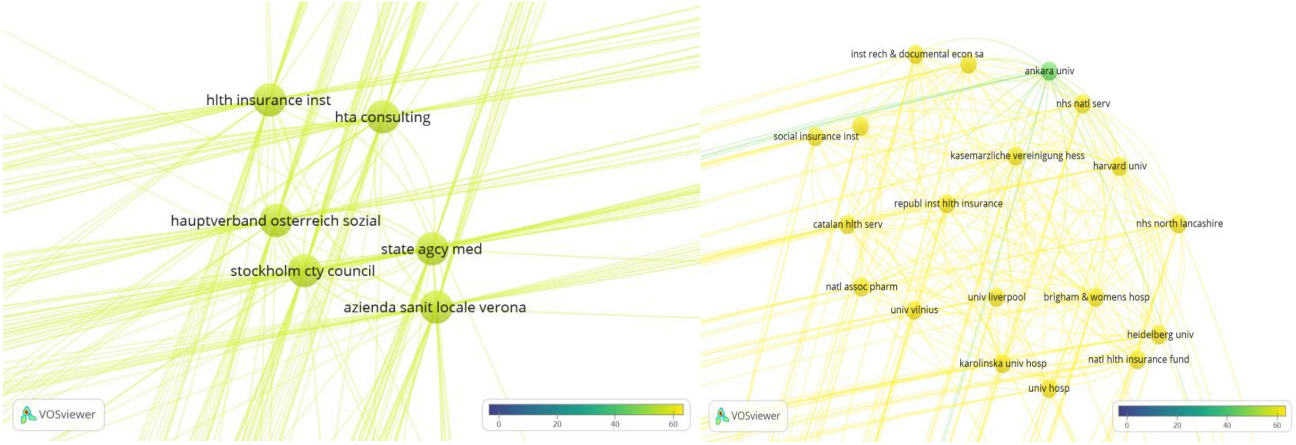
| R | Institution $_{(ND)}$ | ND | Institution $_{(NC)}$ | NC | Institution $_{(TLS)}$ | TLS |
|---|---|---|---|---|---|---|
| 1 | Pennsylvania Commonwealth System of Higher Education | 12 | Cyprus University of Technology | 638 | Azienda Sanit Locale Verona | 6155 |
| 2 | State University System of Florida | 12 | Universite de Jijel | 638 | Hauptverband Osterreich Sozialversicherungstrager | 6155 |
| 3 | University System of Georgia | 10 | IRCCS Mario Negri | 271 | Hlth Insurance Inst | 6155 |
| 4 | Georgia Institute of Technology | 8 | Carnegie Mellon University | 247 | HTA Consulting | 6155 |
| 5 | University of Florida | 8 | Amirkabir University of Technology | 215 | State Agcy Med | 6155 |
| 6 | Carnegie Mellon University | 7 | University of Ontario Institute of Technology | 215 | Stockholm County Council | 6155 |
| 7 | United States Department of Energy Doe | 7 | Universiti Teknologi MARA | 210 | IRCCS Mario Negri | 4686 |
| 8 | University of Pittsburgh | 7 | Universidad de Jaen | 210 | Karolinska Institutet | 4426 |
| 9 | University of Texas System | 7 | University of Melbourne | 165 | University of Strathclyde | 4426 |
| 10 | Rutgers State University New Brunswick | 6 | University of Sydney | 165 | Utrecht University | 3915 |

In Figure 9, we visualize the bibliographic coupling between institutions by setting the weight and scores as TLS and the average number of citations (AC), respectively. In other words, the more common references cited in the publications of the institution between other institutions, the larger the node representing it, and the higher the NC of the institution, the closer its node and links are to the yellow in the color bar. Most of the purple nodes scattered around a certain distance from the center barely have bibliographic coupling relationship with other institutions, and their NC are low as well. Again, we zoom in the area pointed by the arrow to highlight the sub-networks composed of institutions that performed well on the two indicators TLS and NC. The Figure 9 (b) reveals that these 6 institutions have a high degree of overlap with other institutions in terms of bibliographic coupling, that is, they can be regarded as the mainstream in the EE field to a certain extent. The green color brought by the high citation also shows the quality of their publications guaranteed. And the Figure 9 (c) proves that highly cited institutions also have complex bibliographic coupling with others, indicating a positive correlation relationship between TLS and NC.

From this analysis, we should realize that scholars and practitioners in the field of EE should keep abreast of the research dynamics of outstanding institutions, learn from their research methodologies, and actively seek cooperation with them to promote the development of more relevant institutions.



**(a)** Overview



**(b)** The top 6 institutions with the highest TLS

**(c)** A relatively concentrated highly-cited sub-network

**Figure 9**. The Institutions Bibliographic Coupling Overlay Network based on TLS and AC

### *Sources Level*

In this part, we first select the top 10 publication sources with the highest citations, and summarize detailed information on relevant representative indicators in Table 4 to show their influence in the EE field, including the partition(s) in Journal Citation Reports (JCR) and the newest impact factor ($IF_{2022}$). Compared with the *ASEE Annual Conference Exposition* (ND: 28) and *Engineering Economist* (22), which are the only two publication sources owning more than 10 documents, the output of the 10 sources on the list is not eye-catching. This does not make them less authoritative, on the contrary, it reflects the high quality of their output. In various of categories involved, 7 journals belong to the Q1 partition under every corresponding category, and none of the rest are below Q2 partition. In particular, the *Progress in Energy and Combustion Science* has been widely and comprehensively recognized.

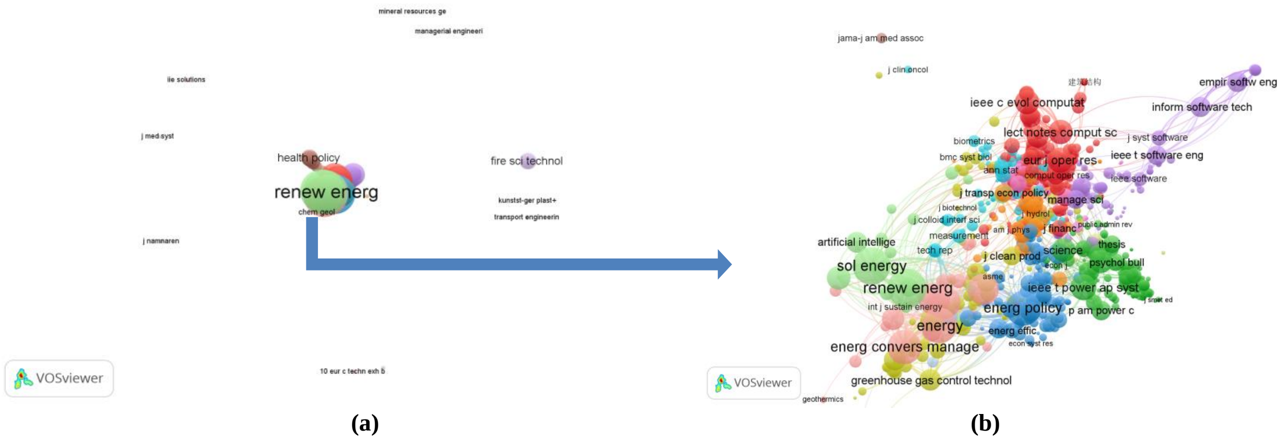
Table 4

**The top 10 Most Influential Sources Based on NC in EE**

| R | Source | NC | ND | Categories | JCR partition | IF$_{2022}$ |
|---|---|---|---|---|---|---|
| 1 | *Progress in Energy and Combustion Science* | 765 | 2 | Energy & Fuels; Engineering, Chemical; Engineering, Mechanical; Thermodynamics | Q1; Q1; Q1; Q1 | 29.5 |
| 2 | *Renewable and Sustainable Energy Reviews* | 308 | 5 | Energy & Fuels; Green & Sustainable Science & Technology | Q1; Q1 | 15.9 |
| 3 | *IEEE Transactions on Software Engineering* | 307 | 5 | Computer Science, Software Engineering; Engineering, Electrical & Electronic | Q1; Q1 | 7.4 |
| 4 | *Information Sciences* | 274 | 2 | Computer Science, Information Systems | Q1 | 8.1 |
| 5 | *Journal of Cleaner Production* | 177 | 2 | Engineering, Environmental; Environmental Sciences; Green & Sustainable Science & Technology | Q1; Q1; Q1 | 11.1 |
| 6 | *Science and Engineering Ethics* | 163 | 1 | Engineering, Multidisciplinary; Ethics; History & Philosophy of Science; Multidisciplinary Sciences | Q2; Q1; Q1; Q2 | 3.7 |
| 7 | *BMC Systems Biology* | 161 | 1 | Mathematical & Computational Biology | Q2 | 2.048$_{(2018)}$ |
| 8 | *Waste Management* | 149 | 1 | Engineering, Environmental; Environmental Sciences | Q1; Q1 | 8.1 |
| 9 | *Machine Learning* | 146 | 1 | Computer Science, Artificial Intelligence | Q2 | 7.5 |
| 10 | *IEEE Transactions on Power Systems* | 145 | 9 | Engineering, Electrical & Electronic | Q1 | 6.6 |

Furthermore, we generate the co-citation network of publication sources in Figure 10. In order to display as many co-citation relationships between different sources as possible, we set the minimum number of citations of a source as 3, and a total of 905 sources meet the threshold. Also, we still set the weights as TLS, which means the more a source is cited together with other sources, the larger the node representing it will be. In Figure 10 (a), the *Renewable Energy* (TSL: 12340, NC: 120) occupies an absolute central position because its TLS is far ahead of other sources while the small nodes scattered around have no co-citation links with others. Except for the lavender node on the right side, under which there are 5 fire-related publication sources.

Observing the Figure 10 (b) carefully, among the light green, pink and navy-blue clusters that mainly represent the energy field, the Solar Energy (10769, 81), Energy (9187, 104), Energy Conversion and Management (8268, 74) and Applied Energy (7809, 82) are the remaining members of the top 5 sources of TSL. Moreover, other easily distinguishable clusters include domains of power engineering, computer, software, chemical engineering and technology-related fields represented by emerald green, red, purple, yellow, orange and sky blue respectively, which embodies the characteristic of the convergence of multiple disciplines in the EE field and is consistent with the many classifications covered in Table 4. Through the co-citation analysis of publication sources, we realize that most of the source in Figure 10 are correlated with the core theme of environment. Indeed, in the face of increasingly severe ecological and environmental problems including energy crisis, greenhouse effect and pollution prevention, it is necessary to simultaneously consider multiple factors and use multiple advanced technologies to cope with complex problems in EE field.



(a) (b)

**Figure 10.** The Co-Citation Network of Publication Sources Based on TLS

### *Authors Level*

The progress and innovation of any discipline are inseparable from the continuous exploration and study of countless scholars. Frequently summarizing the research results of the predecessors and paying close attention to the latest developments of scholars will help us grasp the development trend of the field. For this purpose, we have listed detailed information about the top 12 authors with the highest ND in Table 5 as well as their average publish year (APY) and H-index.

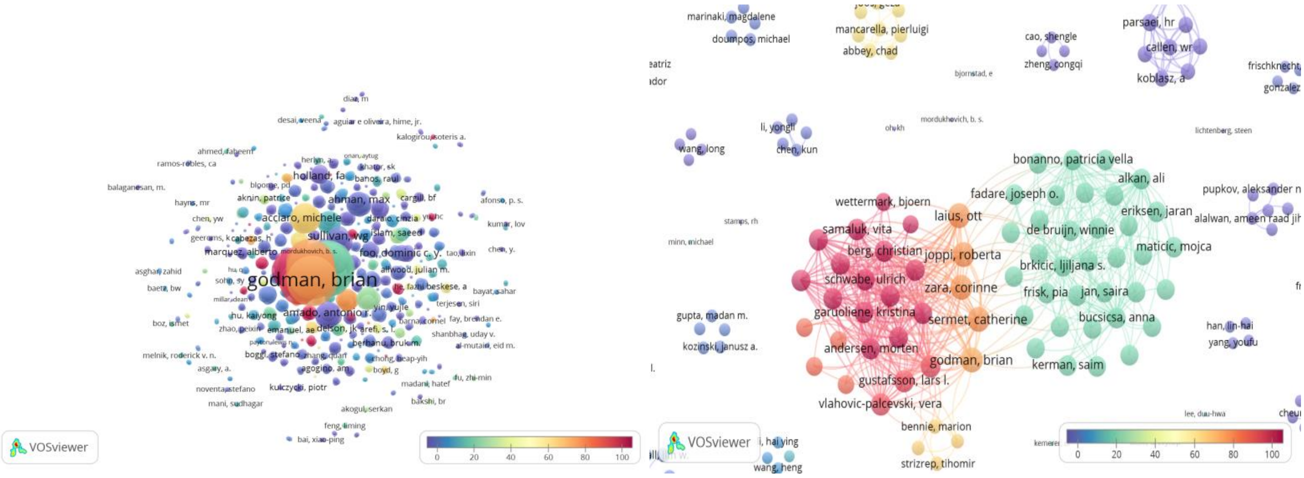
As shown in Table 5, the distribution of ND is more even while the difference of NC is more significant, which makes the ND/NC of the last six authors increase evidently compared with the first six authors in the table. Godman, B., comparatively speaking, maintains high-quality output and the publication time is relatively recent. Behind the last three authors on the list, there are three important publications, including 2 articles and 1 review. All three documents take policies to improve the European prescription efficiency as a common theme of discussion, taking into account both engineering and economic considerations (Vončina *et al*., 2011; Godman *et al*., 2010; Godman *et al*., 2011). Similar to IF, H-index is inapplicable to interdisciplinary comparison, but it can at least directly show the author's personal high influence when the value is high enough, such as Godman, B., Kahraman, C. and Gustafsson, L. L.

Table 5

**The Top 12 Most Productive Authors in EE**

| R | Author | ND | NC | NC/ND | APY | H-index |
|---|---|---|---|---|---|---|
| 1 | Eschenbach, T. | 7 | 12 | 1.71 | 2011 | 7 |
| 2 | Sullivan, W. G. | 6 | 15 | 2.50 | 1994 | 9 |
| 3 | Holland, F. A. | 6 | 1 | 0.17 | 1973 | 17 |
| 4 | Watson, F. A. | 6 | 1 | 0.17 | 1973 | 11 |
| 5 | Lewis, N. A. | 5 | 11 | 2.20 | 2011 | 4 |
| 6 | Wilkinso, J. K. | 5 | 1 | 0.20 | 1973 | 1 |
| 7 | Godman, B. | 4 | 292 | 73.00 | 2012 | 40 |
| 8 | Kahraman, C. | 4 | 132 | 33.00 | 2004 | 58 |
| 9 | Ramasubbu, N. | 4 | 53 | 13.25 | 2015 | 14 |
| 10 | Bishop, I. | 3 | 270 | 90.00 | 2010 | 13 |
| 11 | Gustafsson, L. L. | 3 | 270 | 90.00 | 2010 | 49 |
| 12 | Vlahovic-Palcevski, V. | 3 | 270 | 90.00 | 2010 | 25 |

After we set the weights to TLS and the scores to AC, the co-authorship overlay network of 991 authors who have published at least one document and obtained one citation is shown in Figure 11. Not surprisingly, Godman, B. (TLS: 92, NC: 292) has the most collaborations with other authors, followed by Joppi, R. (85, 228), Laius, O. (85, 228), Sermet, C. (85, 228), Zara, C. (85, 228), Bishop, I. (53, 270), Gustafsson, L. L. (53, 270), Vlahovic-Palcevski, V. (53, 270), Andersen, M. (46, 206) and Berg, C. (46, 206). When we have a close-up view of the central and adjacent parts in Figure 11 (a), each sub-network, larger or smaller, appears as a relatively independent flower ball shape. One can easily infer that the authors prefer cooperating with familiar partners repeatedly. Considering the continuity and professionalism of the research work, this phenomenon is reasonable and predictable. Nevertheless, we still encourage more cooperations with different scholars to get out of the comfort zone, so that different sparks can be collided during the process and the innovation and development of the field can be realized.



(a) (b)

**Figure 11.** The Co-Authorship Overlay Network of Authors Based on TLS and AC

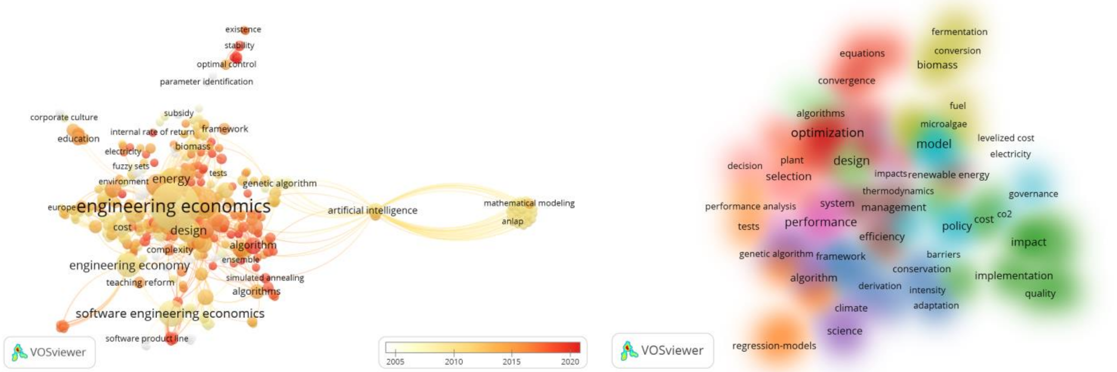
### *Keywords Analysis*

To further explore the popular topics and potential directions for future research, in this subsection, we conduct the co-occurrence analysis and burst detection analysis on keywords and present the high frequency keywords with word clouds. Both keyword co-occurrence and burst detection analyses are able to capture the dynamics of research hotspot variation over time in the field of EE, while the word cloud results are a concentrated display of popular topics in recent years.

### *Co-Occurrence Analysis*

Keywords are refined summaries of the full text, and the co-occurrence analysis on them therefore enables us to not only quickly identify the topics of different documents, but also comprehend the closeness of the connection between the topics. In Figure 12 (a), we present the co-occurrence network of all keywords of which 334 keywords meet the requirement of co-occurring more than twice and having link(s) with other items. The top 10 keywords with the most co-occurrences are engineering economics (co-occurrence: 67, TSL: 165), optimization (30, 113), software engineering economics (20, 62), engineering economy (17, 40), design (16, 68), model (15, 55), performance (14, 55), energy (14, 50), policy (12, 43), and economics (12, 34). Combined with other prominent keywords in the figure, we can capture the message that the EE field is developing towards intelligence. Energy issues have also triggered a lot of thinking during the past decade.

After adopting the same parameter settings, 123 words and phrases form the co-occurrence density network of keywords plus in Figure 12 (b). The main 5 clusters include cluster 1 (red) with "optimization" as the core, cluster 4 (yellow) with "energy" as its core, cluster 6 (sky blue) with "model" as its core, cluster 9 (fuchsia) with "performance" as its core, and cluster 11 (light green) with "design" as its core. In addition to the information that has been conveyed from (a), we can also notice that the EE industry has gradually shifted its focus to the early design stage, while paying attention to performance that can be improved with the times.



**(a)** **(b)**

**Figure 12.** The Co-Occurrence Overlay Network of Keywords Considering APY

### *Burst Detection Analysis*

To trace the emerging trends in the literature, we visualize the keywords via burst detection analysis in CiteSpace, and sort the results of the top 16 keywords with the strongest citation burst in Table 6. During the period from 2000 to 2021, the keyword "system" can be considered owning the highest strength, more importantly, it appears in the relatively newest time. In contrast, the keyword "fuzzy number", "mathematical programming" and "software product line" though had burst for longer time, they have shown more stable and long-term development tendencies after being brought up in the beginning of 21st century, rather than leading explosive discussion every now and then. Different from the burst situation of other keywords, "risk" has obviously always been the focus of research. The emphasis on "risk analysis" concentrated in the beginning of the century has resulted in a burst for the longest time of 8 continuous years. Now, there is a more comprehensive understanding of risk and its management and control.

Table 6

**Top 16 Keywords with the Strongest Citation Bursts**

| R | Keywords | Strength | Begin | End | 2000-2021 |
|---|---|---|---|---|---|
| 1 | engineering economics | 3.26 | 2012 | 2014 | ▬▬▬▬▬▬▬▬▬▬▬▬🟥🟥🟥▬▬▬▬▬▬▬ |
| 2 | system | 2.91 | 2019 | 2021 | ▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬🟥🟥🟥 |
| 3 | artificial intelligence | 2.03 | 2008 | 2010 | ▬▬▬▬▬▬▬▬🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬ |
| 4 | fuzzy number | 1.94 | 2000 | 2004 | 🟥🟥🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬ |
| 5 | mathematical programming | 1.83 | 2004 | 2007 | ▬▬▬▬🟥🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬▬▬▬ |
| 6 | software product line | 1.77 | 2001 | 2007 | ▬🟥🟥🟥🟥🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬▬▬▬ |
| 7 | productivity | 1.75 | 2004 | 2007 | ▬▬▬▬🟥🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬▬▬▬ |
| 8 | risk analysis | 1.75 | 2000 | 2007 | 🟥🟥🟥🟥🟥🟥🟥🟥▬▬▬▬▬▬▬▬▬▬▬▬▬▬ |
| 9 | risk | 1.66 | 2016 | 2019 | ▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬▬🟥🟥🟥🟥▬▬ |

| R | Keywords | Strength | Begin | End | 2000-2021 |
|---|---|---|---|---|---|
| 10 | education | 1.63 | 2013 | 2015 | ▂▂▂▂▂▂▂▂▂▂▂▂▂███▂▂▂▂▂▂ |
| 11 | chaos theory | 1.63 | 2013 | 2015 | ▂▂▂▂▂▂▂▂▂▂▂▂▂███▂▂▂▂▂▂ |
| 12 | classification | 1.62 | 2011 | 2017 | ▂▂▂▂▂▂▂▂▂▂▂███████▂▂▂▂ |
| 13 | energy | 1.61 | 2012 | 2015 | ▂▂▂▂▂▂▂▂▂▂▂▂████▂▂▂▂▂▂ |
| 14 | implementation | 1.58 | 2010 | 2011 | ▂▂▂▂▂▂▂▂▂▂██▂▂▂▂▂▂▂▂▂▂ |
| 15 | case study | 1.57 | 2018 | 2019 | ▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂██▂▂ |
| 16 | uncertainty | 1.57 | 2018 | 2019 | ▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂▂██▂▂ |

### *High-Frequency Keywords*

At last, we create word clouds of author keywords and keywords plus of which the APY are in the range of 2017 and 2021 in Figure 12. Keywords with higher AC are represented by more conspicuous sizes and colors, and the repeated ones are deleted so that the information in (a) and (b) can complement each other. Compared with the analysis of research directions, keywords can further lead us to the specific concerns in different directions. In particular, the keywords selected here are relatively new in time, which can better support the prediction of future development trends in the short term.

Combining the key points of the two pictures, we receive the following main messages: Firstly, keywords such as “machine learning”, “swarm intelligence”, “software” and “neural networks” reveal the importance and necessity of digital and information technology for EE to keep up with the pace of the times and successfully complete the intelligent transformation. Secondly, “climate policy”, “wind turbine”, “electricity”, “renewable energy”, etc. once again emphasize that environmental and energy issues need to be resolved urgently. Thirdly, “metaheuristics”, “algorithm”, “regression-models”, etc. indicate that the analysis involved in EE rely on mathematical techniques to guarantee the accuracy and credibility of results. Finally, “circular economy”, “optimization”, “risk”, “payback period”, “prediction”, “internal rate of return”, etc. are reminders for us to strive for the improvement in traditional theory and technology. We need to focus on proactive observation and management as well as ensuring that benefits are maximized. Under the turbulent torrent of development of society and science, EE needs to adopt the right “strategy” to fulfill the “transformation” and “evolution”.

**(a)** Author keywords **(b)** Keywords plus

**Figure 13.** The Co-Occurrence Overlay Network of Keywords Considering APY

## Discussion

### *Hot Spots and Practical Significance*

Based on the analysis that has been completed, in this subsection, we plan to review four highly discussed topics and investigate their implications.

### *Software Engineering*

Among all those publications analyzed above, the frequency of research related to software engineering is high, especially in the last ten years. The topics include but are not limited to technical debt management (Ramasubbu & Kemerer, 2019), social aspects of development process (Yilmaz & O'Connor, 2011), the return on a software-evolution investment (Tansey & Stroulia, 2010), quality management (Ramasubbu & Kemerer, 2019), cloud computing (Fokaefs *et al.*, 2017; Si *et al.*, 2023), and fault prediction (Kumar & Sureka, 2017). Tools and theories such as empirical study (Cruz *et al.*, 2019; Li *et al.*, 2023), machine learning models (Kumar & Sureka, 2017; Sonabend *et al.*, 2021), game theory (Chen & Larbani, 2006; Adler *et al.*, 2021) have been applied to explore and solve different projects or practical issues. Similarly, the literature on computing engineering economics as research object is also emerging in large numbers, which can be regarded as an obvious sign and an expected development trend of the Internet era.

We are now in an age where technology is rapidly becoming more and more advanced. The powerful functions of computer technologies, such as digital modeling and machine learning, have given birth to a large amount of high-quality software. They make the management and optimization of various projects more intelligent and precise, which helps to better ensure the achievement of economic and quality objectives. In addition, it is well recognized that software development can be seen as a form of social activity based on knowledge, which reminds us to value social interactions and behaviors of individuals and teams that contribute to organizational performance and productivity improvement (Yilmaz & O'Connor, 2011). Thus, theoretical and practical research around software engineering has the potential to be a powerful driver of progress and transformation in the field of EE.

We should focus on the positive attempts that scholars have already made in this direction. For example, considering that an important indicator of productivity measurement in software engineering economics is delivery speed, Ventura-Molina *et al*. (2020) proposed an algorithm based on data analysis called search method based on feature construction (SMFC) to predict the performance of this indicator in software enhancement projects. Cruz *et al*. (2019) presented a systematic mapping study on replications of empirical studies in SE from 2013 to 2018, which helped to learn about the most popular forums used for publishing replications, and the research gaps as well as development trends in relevant areas. In a business world where all participants compete fiercely to survive, software engineers should prepare in time digital solutions that is consistent with the business goals of the company and is able to take advantage of the company's unique strength, so the digital transformation can proceed smoothly (Sanchez-Segura *et al*., 2021). Based on such demand, Sanchez-Segura *et al*. (2021) provided a method based on business model canvas and a corresponding simulation tool to identify and evaluate the intangible assets that affect the decision-making on the digital solutions. The software-based trend is rising, which is not only to meet the needs of the overall environment, but also the inevitable development direction of the EE itself to enter a higher level of production, management and control.

### *Environmental Theme*

With the advancement of technology and the development of social economy, people all over the world are enjoying both material and spiritual satisfaction, while the world is facing thorny problems such as environmental pollution, resource shortage and global climate warming (Ding *et al*., 2013; Zhang *et al.*, 2021). Fortunately, people have realized the importance of environmental protection and resource conservation as well as sustainable development (Qian *et al*., 2023b). Although today’s prosperity is almost based on the excessive consumption of resources and the sacrifice of the living environment, we after the economic takeoff may have stronger motivation and greater ability to make up for the mistakes of the past and then create a better future. Nowadays, when we talk about environmental engineering economics, it means not only to achieve a balance between economic goals and environmental goals, but also to explore how to improve economic and social benefits through greener methods. The field of EE also bears responsibility for shaping principles of practice that are more responsive to sustainable development and for developing cleaner technologies.

Around the theme of environmental protection, scholars in the field have conducted a lot of in-depth and fruitful research. For instance, dealing with the sewage treatment, Chen *et al*. (2014) analyzed the costs and influencing factors of treatment projects, then proposed countermeasures to improve the economic efficiency for projects construction and operation based on the theory of life circle costing. In the face of global warming and climate change, one viable option is to improve material efficiency, which means pursuing reduction in the production of high-volume energy-intensive materials (Allwood *et al*., 2013). As for energy shortages, renewable energies, the circular economy and other specific measures (e.g., green buildings) have begun to play a role as effective responses (Ding *et al*., 2013). The step into the 21st century has coincided with a consciousness shift that has placed emphasis on the sustainable development (Barboza, 2015). There is no doubt that the green transformation would pose additional challenges for the further development of EE and would require considerable knowledge, technology and spiritual strength to overcome the attendant difficulties. Many policies have been put in place to support and monitor the whole process, but there is still a need for greater cooperation between countries in order to achieve a thriving green economy through vibrant innovation while fulfilling environmental tasks such as energy conservation and emissions reduction.

### *Educational Research*

Any science that wants to move from suspended academic discussion to practical popularization among the general public and form into promising industry productivity is inseparable from the dissemination and implementation of basic knowledge through education, which not only ensures that the previous academic achievements can be inherited but also promotes more innovation in the process of cultivating talents. To all intents and purposes, higher education is seen as the primary driving force for the first productive force of science and technology and the first resource for qualified personnel and innovation (Li, 2018). EE is an interdisciplinary subject that encompasses a wide range of content while constantly incorporating new knowledge and tools to keep up with the times. How to adjust the teaching method and change the teaching focus so as to meet the practical needs in educational activity related to EE has been a hot topic within the field.

Among the various educational articles that focus on EE courses, some of them attempted to innovate teaching methods or reform teaching content, and others just took the teaching process or learning effect of the course as samples for research in other directions. The emphasis on EE-related courses shows the high expectations for the further growth in this field. Therefore, we can see that there are scholars designing and implementing multiple pedagogical interventions in a postgraduate EE course which aimed at enhancing capability or focused on blending learning, following which the students rated their experiences through an online questionnaire that considered many aspects including the impact caused by COVID-19 pandemic (Walwyn & Combrinck, 2021). Moreover, the education form has gradually progressed from the blackboard to learning through the Internet from quite a long time ago (Rane & Mackenzie, 2020), which leads to a wide range of discussion on online learning methods and tools. No matter it's video learning and quick response (QR) code (Ahmed & Zaneldin, 2019), online testing modules (Rane & Mackenzie, 2020) or other technologies, any one of them is worth trying or even in-depth research for better learning effect. Plouff and Barakat (2012) applied distance learning in a pilot study to deliver students with professional and academic content that contained EE, after which they gained the result of an increase in students' knowledge for all topic areas by conducting direct and indirect assessment methods. EE education has a wide range of content and is tightly connected to the development of digital technology, computer drawing tools, engineering cost software, digital modeling, etc. With regard to the modes of education that would have a significant impact on the future development of EE, we need to explore new paths, improve the old ways and achieve a rapid transition between the old and the new modes through long-term research and demonstration.

### *Applications of Fundamental Principles, Theories and Technologies*

EE is a discipline with strong practicality and application. Its principles and theories have become more mature, and the tools and methodologies of EE are also widely utilized in specific engineering projects and other fields of knowledge.

The types of specific engineering projects are very diverse. The scale can be as large as water system (Wu *et al*., 2010; Ortloff, 2023), highway management (Li, 2009; Wang *et al*., 2023), electric power distribution systems (Heydt, 2017; Li *et al*., 2023), etc., or as small as energy efficiency improvement of room air conditioners (Mahlia, 2010; Kwon & Jeong, 2023) and slope optimization (Fang *et al*., 2019), all of which would consume a great many manpower and financial resource in design, construction and operation. To discuss and address EE problems in specific projects, first of all, we must have a holistic understanding of the engineering project. It is conducive to identify unsolved issues and the economic or technical indicators that need to be accomplished. Next, we need to select appropriate principles, models and/or algorithms from EE for comparison and analysis of alternatives. Finally, the research results are given and accompanied by suggestions or final conclusions provided in further discussions.

The usefulness of a great deal of EE knowledge has already been recognized in the wide range of scenarios in which it has been applied. Traditional ones include cost-benefit analysis (Pinto *et al*., 2011; Boltürk & Seker, 2022), replacement analysis (Balaganesan & Ganesan, 2020), life circle cost analysis (List, 2007; Riotto *et al*., 2021), breakeven analysis (Jung & Biletskiy, 2009), sensitivity analysis (Xu *et al*., 2020), commodity price simulation (Davis, 2012). They are also often used in conjunction with knowledge from other fields, such as grey theory (Liu, 2020; Zhang *et al*., 2020) and Monte Carlo simulation (Sarfaraz, 2006; Liu *et al*., 2023), which contributes to update and enrich the EE toolbox. Now the concept of new engineering emphasizing characteristics of qualitative regularity, leading, generalized, forward-looking, cross-cutting, open, practical has been put forward in order to spawn and lead the new economy by providing a large pool of new technologies (Li, 2018).

### *Future Research Directions and Problems to be Solved*

Based on current research hotspots, we continue to predict the future research directions in the short term and point out a few problems waiting to be overcome.

*Convergence and Development of Emerging Technologies*

Software engineering is closely related to computer science and Internet technology, which has triggered its rapid growth in today's Internet era. Current research hot spots contain a variety of techniques such as machine learning (ML), deep learning (DL), natural language processing (NLP), neural network prediction (NNP) under the field of artificial intelligence (Ahmed et al., 2022), the data mining and massively parallel processing (MPP) under big data, and cloud computing under the field of Internet of Things (IoT), etc.

Realizing smooth integration with advanced technologies in the software development process, and then producing stable and accurate representative software that are capable of reaching the economic efficiency requirements in different circumstances are both tough challenges waiting for researchers to work on in the future. In the meantime, distinguishing the economic nature of software engineering itself and economic effects such as cost control achieved in engineering practice relying on software are also aspects worth noting.

### *Low-Carbon Initiatives and Actions*

Achieving sustainable development has become a global consensus. Among the various environmental issues, "carbon" is definitely one of the elements at the center. Human's excessive consumption of traditional fossil fuels have significantly increased the concentration of $CO_2$ in the atmosphere, which has caused global warming and other abnormal climate changes (Zhu & Zhao, 2013). To this point, we are eager to find safe, clean and efficient alternative energy sources while developing green mode of production and lifestyles that satisfy energy-saving and emission-reducing demands to deal with a series of consequences such as glaciers melting, sea level rising, and desertification. For EE, activities related to environmental engineering will inevitably raise the bar for development in this field. Increasingly strict regulations and severe ecological environment are pushing EE to realize effective green innovations that are in line with reality.

In September 2020, China committed to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060, which shows China's firm determination to actively participate in and lead global climate governance and promote the construction of ecological civilization. However, the double carbon goals can be formidable challenges for any country around the world, not to mention that for China, the world's largest developing country with a coal-based energy mix. To overcome the obstacles to achieving carbon peaking and carbon neutrality, on the one hand, we must insist on reducing emissions by implementing energy structure adjustments, such as the transformation of energy and emission-intensive industries towards zero emissions

(Nilsson *et al*., 2021). On the other hand, we must also pay attention to biological carbon sequestration measures to give full play to the role of the ecosystem (Gao *et al*., 2021).

Studies on the low-carbon theme within the scope of EE can pay more attention on the development of materials or methods for carbon capture and sequestration, such as membrane materials (Khalilpour *et al*., 2015; Youns *et al*., 2023) and thermal hydrogen energy systems (Moore, 2017; Martis *et al*., 2021). Besides, more time and resources should be devoted to the transformation of green industries. For example, both the construction and transport sectors account for a large proportion of the total carbon emissions, so quantifying carbon consumption indicators to explicitly estimate the low carbon effect of virescence of engineering projects, as well as carrying out green design for ecological concerns and landscape effects are both tricky problems worth exploring (Shen *et al*., 2013). Economy can be embodied in the cost savings during the development process of new green technologies and in the wealth creation of environmentally friendly new industrial ecology.

## Conclusion

In this paper, we looked back the development of the EE domain and presented a comprehensive overview of the global research endeavor. EE was born to assist engineers make correct economic decisions in specific engineering projects, or it can be described as the engineering interpretation for achieving economic benefits. With engineering and economics as the vigorous components and drivers, the connotation of EE has been increasingly rich and complex. Yet, for an interdisciplinary subject to prove its existence value, it is necessary to create unique features and capacities to deal with new circumstances. As the technology level of the new century is getting higher and higher, EE has also made considerable progress in terms of publication volume and innovation, and unprecedented difficulties have also come along. It is necessary to focus on accurately grasping the dynamics of social development and continuously incorporating knowledge and technologies in emerging fields.

By applying two main visualization tools, Vosviewer and CiteSpace, we examined the characteristics of the 624 publications extracted from 1915 to 2021 from multiple dimensions. It is clear that researchers have been investing a lot of effort into promoting the progress of this field and striving to be innovative while attaching importance to the combination of knowledge with related fields. The result also confirmed that scholars in this field are trying to ride on the wave of the digital age and make full use of smart technology to pursue more precise and exhaustive outcome. Meanwhile, environmental factors, which have significant impacts on engineering and economics, now have become even more essential for making breakthroughs and substantial changes in the field of EE.

Overall, this study analyzed these phenomena from various perspective and gave corresponding interpretations. With the help of figures and tables, the authors, sources, institutions, and countries/regions that excel in the vast body of research related to EE are clearly presented, and the longstanding hot topics and emerging themes in the field are basically reflected by the keywords analyses. Although no direct answer has been offered, we hope it can turn into effective reference or indirect resource to build researchers a bridge to the past and to bring some inspiration and ideas to the future.

## Acknowledgments

The work was supported by the National Natural Science Foundation of China (Nos. 72071135 and 72271173), the National Social Science Fund of China (22FGLB005), the Ministry of education of Humanities and Social Science project (No. 21YJC630030), and the China Postdoctoral Science Foundation (No. 2020M680151, 2023T160459).

## References

Adler, N., Brudner, A., & Proost, S. (2021). A review of transport market modeling using game-theoretic principles. *European Journal of Operational Research*, 291(3), 808–829. https://doi.org/10.1016/j.ejor.2020.11.020

Adriaanse, L. S., & Rensleigh, C. (2013). Web of Science, Scopus and Google Scholar: A content comprehensiveness comparison. *The Electronic Library*. 31(6), 727–744. https://doi.org/10.1108/EL-12-2011-0174

Afolalu, S. A., Okwilagwe, O., Emetere, M. M., & Ikumapayi, O. M. (2021). Impact and optimisation of a new paradigm in engineering economics for sustainable manufacturing operations. *Materials Today*: *Proceedings*, 44, 2889–2894. https://doi.org/10.1016/j.matpr.2021.01.098

Ahmed, A., Boopathy, P., & Rajan, S. S. (2022). Artificial intelligence for the novel corona virus (COVID-19) pandemic: Opportunities, Challenges, and Future Directions. *International Journal of E-Health and Medical Communications (IJEHMC)*, 13(2), 1–21. https://doi.org/10.4018/IJEHMC.20220701.oa5

Ahmed, W., & Zaneldin, E. (2019). Blending QR code with video learning in the pedagogical process for the college foundation level. *Interactive Technology and Smart Education*, 17(1), 67–85. https://doi.org/10.1108/ITSE-08-2019-0043

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2013). Material efficiency: Providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(1986), 20120496. https://doi.org/10.1098/rsta.2012.0496

Aydin, S., Kahraman, C., & Kabak, M. (2018). Evaluation of investment alternatives using present worth analysis with simplified neutrosophic sets. *Inzinerine Ekonomika-Engineering Economics*, 29(3), 254–263. https://doi.org/10.5755/j01.ee.29.3.19392

Backhouse, R. E., & Medema, S. G. (2009). Retrospectives: On the definition of economics. *Journal of economic perspectives*, 23(1), 221–233. https://doi.org/10.1257/jep.23.1.221

Balaganesan, M., & Ganesan, K. (2020). Fuzzy approach to determine optimum economic life of equipment with change in money value. *Cognitive Informatics and Soft Computing*, 647–655. https://doi.org/10.1007/978-981-15-1451-7_66

Banga, J. R. (2008). Optimization in computational systems biology. *BMC systems biology*, 2(1), 1–7. https://doi.org/10.1186/1752-0509-2-47

Barboza, C. (2015). Towards a renewable energy decision making model. *Procedia Computer Science*, 44, 568–577. https://doi.org/10.1016/j.procs.2015.03.017

Boehm, B. W. (1984). Software engineering economics. *IEEE transactions on Software Engineering*, (1), 4–21. https://doi.org/10.1109/TSE.1984.5010193

Bolturk, E., & Seker, S. (2022). Spherical fuzzy present worth analysis method for emergency hospital investment analysis. *IEEE Transactions on Engineering Management*. 70(8), 2891–2902. https://doi.org/10.1109/TEM.2022.3190914

Bussey, L. E. (1978). The economic analysis of industrial projects. Prentice-Hall, Englewood Cliffs.

Burns, J., White, B., & Konstant, A. (2020). Engineering economy as a vibrant and relevant course in the engineering programs of today and tomorrow. *The Engineering Economist*, 65(3), 236–258. https://doi.org/10.1080/0013791X.2020.1781309

Chen, H. G., Li, C. Y., & Xie, D. D. (2014). Economic study on sewage treatment engineering based on LCC. *Advanced Materials Research*, 838/841, 2689–2693. https://doi.org/10.4028/www.scientific.net/AMR.838-841.2689

Chen, Y. W., & Larbani, M. (2006). Two-person zero-sum game approach for fuzzy multiple attribute decision making problems. *Fuzzy Sets and Systems*, 157(1), 34–51. https://doi.org/10.1016/j.fss.2005.06.004

Cruz, M., Bernardez, B., Duran, A., Galindo, J. A., & Ruiz-Cortes, A. (2019). Replication of studies in empirical software engineering: A systematic mapping study, from 2013 to 2018. *IEEE Access*, 8, 26773–26791. https://doi.org/10.1109/ACCESS.2019.2952191

Davis, G. A. (2012). Technical note: Simulating the two-factor Schwartz and Smith model of commodity prices. *The Engineering Economist*, 57(2), 130–140. https://doi.org/10.1080/0013791X.2012.677302

Dean, J. (1951). Capital budgeting. Columbia University Press. https://doi.org/10.7312/dean90552

DeGarmo, E. P., Sullivan, W. G., & Bontadelli, J. A. (1989). Engineering Economy (Eighth Edition), Macmillan Publishing Co., New York.

Ding, W. X., Zhao, Y. H., & Ji, X. (2013). Analysis of the environmental benefits of green building. Applied Mechanics and Materials, 368-370, 1135–1138. https://doi.org/10.4028/www.scientific.net/AMM.368-370.1135

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021a). How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research, 133, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Donthu, N., Kumar, S., Pandey, N., & Lim, W. M. (2021b). Research constituents, intellectual structure, and collaboration patterns in Journal of International Marketing: An analytical retrospective. Journal of International Marketing, 29(2), 1–25. https://doi.org/10.1177/1069031X211004234

Duarte, P. G., & Giraud, Y. (2020a). Introduction: From "Economics as Engineering" to "Economics and Engineering". History of Political Economy, 52(S1), 10–27. https://doi.org/10.1215/00182702-8717898

Duarte, P.G., & Giraud Y. (Eds.) (2020b). Economics and engineering: Institutions, practices, and cultures. *History of Political Economy*, 52(S1), 1–332.

Fang, H. W., Chen, Y., & Deng, X. W. (2019). A new slope optimization design based on limit curve method. *Journal of Central South University*, 26(7), 1856–1862. https://doi.org/10.1007/s11771-019-4139-y

Fish, J. C. L. (1915). *Engineering economics*: first principles. McGraw-Hill book Company, Incorporated.

Fokaefs, M., Barna, C., & Litoiu, M. (2017). From devops to bizops: Economic sustainability for scalable cloud applications. *ACM Transactions on Autonomous and Adaptive Systems* (TAAS), 12(4), 1–29. https://doi.org/10.1145/3139290

Gao, J. X., Hou, P., Zhai, J., Chen, Y., Gao, H. F., Jin, D. D., & Yang, M. (2021). Promote the "Dual Circulation" through carbon peak and neutrality to realize high-quality economic development. *China Development*(S1), 47–52. https://doi.org/10.15885/j.cnki.cn11-4683/z.2021.s1.006

Gill, F. (1943). Engineering economics. *Journal of the Institution of Electrical Engineers-Part I: General*, 90(33), 373–386. https://doi.org/10.1049/ji-1.1943.0073

Godman, B., Shrank, W., Andersen, M., Berg, C., Bishop, I., Burkhardt, T., ... & Gustafsson, L. L. (2010). Comparing policies to enhance prescribing efficiency in Europe through increasing generic utilization: Changes seen and global implications. *Expert review of pharmacoeconomics & outcomes research*, 10(6), 707–722. https://doi.org/10.1586/erp.10.72

Godman, B., Shrank, W., Andersen, M., Berg, C., Bishop, I., Burkhardt, T., ... & Joppi, R. (2011). Policies to enhance prescribing efficiency in Europe: Findings and future implications. *Frontiers in pharmacology*, 1. https://doi.org/10.3389/fphar.2010.00141

Goldman, O. B. (1920). Financial engineering: A text for consulting, managing and designing engineers and for students. John Wiley & sons, Incorporated.

Grant, E. L. (1930). Principles of engineering economy. New York: Ronald Press Company.

Hebert, R. F. (2021). Prospects for a prigogine alliance between economics and engineering. *Journal of Industrial and Business Economics*, 48(4), 609–614. https://doi.org/10.1007/s40812-021-00198-7

Hess, H. W. (1915). Engineering economics. *ANNALS of the American Academy of Political and Social Science*. 62, 309–310.

Heydt, G. T. (2017). The probabilistic evaluation of Net Present value of electric power distribution systems based on the Kaldor-Hicks compensation principle. *IEEE Transactions on Power Systems*, 33(4), 4488–4495. https://doi.org/10.1109/TPWRS.2017.2764449

Hodder, E., & Jucker, J. V. (1979). A review of: "THE ECONOMIC ANALYSIS OF INDUSTRIAL PROJECTS" by Lynn E. Bussey, Prentice-Hall, Englewood Cliffs, NJ, 1978, 491 pages, $21.95 list. *The Engineering Economist*, 25(2), 146–147. https://doi.org/10.1080/00137917908902846

Jung, H. I., & Biletskiy, Y. (2009). Evaluation and comparison of economical efficiency of HVDC and AC transmission. *2009 Canadian Conference on Electrical and Computer Engineering*, 41–44. https://doi.org/10.1109/CCECE.2009.5090088

Khalilpour, R., Mumford, K., Zhai, H., Abbas, A., Stevens, G., & Rubin, E. S. (2015). Membrane-based carbon capture from flue gas: A review. *Journal of Cleaner Production*, 103, 286–300. https://doi.org/10.1016/j.jclepro.2014.10.050

Khlebnikova, E., Sundar, K., Zlotnik, A., Bent, R., Ewers, M., & Tasseff, B. (2021). Optimal economic operation of liquid petroleum products pipeline systems. *AIChE Journal*, 67(4), e17124. https://doi.org/10.1002/aic.17124

Kliestik, T., Misankova, M., Valaskova, K., & Svabova, L. (2018). Bankruptcy prevention: new effort to reflect on legal and social changes. *Science and Engineering Ethics*, 24(2), 791–803. https://doi.org/10.1007/s11948-017-9912-4

Kumar, L., & Sureka, A. (2017). Analyzing fault prediction usefulness from cost perspective using source code metrics. 2017 *Tenth International Conference on Contemporary Computing* (IC3), 1–7. https://doi.org/10.1109/ IC3.2017.8284297

Kwon, T. D., & Jeong, J. W. (2023). Energy advantage of cold energy recovery system using water-and air-side free cooling technologies in semiconductor fabrication plant in summer. *Journal of Building Engineering*, 69, 106277. https://doi.org/10.1016/j.jobe.2023.106277

Li, D., Wang, Y., & Li, L. (2023). Educational choice has greater effects on sex ratios of college STEM majors than has the greater male variance in general intelligence (g). *Intelligence*, 96, 101719. https://doi.org/10.1016/j.intell.2022.101719

Li, G. H. (2009). Bridge management method based on benefit cost analysis in China. Proceedings of *2009 International Conference of Management Engineering and Information Technology*, 273–276.

Li, L., Xiang, Y., & Lu, Y. (2023). Power system economics course design with energy planning, operation and market cases. *Energy Reports*, 9, 381–390. https://doi.org/10.1016/j.egyr.2023.04.300

List, G. (2007). A model for life cycle evaluation of highway investments. *Structure and infrastructure engineering*, 3(2), 95–101. https://doi.org/10.1080/15732470600590903

Liu, H., Li, S., & Huang, X. (2023). Adaptive surrogate model coupled with stochastic configuration network strategies for time-dependent reliability assessment. *Probabilistic Engineering Mechanics*, 71, 103406. https://doi.org/10.1016/j.probengmech.2022.103406

Liu, J. (2020). A grey theory-based economic prediction method of port and ocean engineering. *Journal of Coastal Research*, 197–200. https://doi.org/10.2112/SI106-046.1

Li, Y. (2018). Research on the education and training mode of innovative talents of new engineering in colleges and universities. *Proceedings of the 2nd International Conference on Culture, Education and Economic Development of Modern Society* (ICCESE 2018). https://doi.org/10.2991/iccese-18.2018.36

Mahdavi, S., Shiri, M. E., & Rahnamayan, S. (2015). Metaheuristics in large-scale global continues optimization: A survey. *Information Sciences*, 295, 407–428. https://doi.org/10.1016/j.ins.2014.10.042

Mahlia, T. M. I., Saidur, R., Husnawan, M., Masjuki, H. H., & Kalam, M. A. (2010). An approach to estimate the life-cycle cost of energy efficiency improvement of room air conditioners. *Energy Education Science and Technology Part A: Energy Science and Research*, 26(1), 1–11. https://doi.org/10.1016/j.ecoleng.2010.07.007

Mariotti, S. (2021a). Forging a new alliance between economics and engineering. *Journal of Industrial and Business Economics*, 48(4), 551–572. https://doi.org/10.1007/s40812-021-00187-w

Mariotti, S. (2021b). A new alliance between the natural and human sciences? In Integration and Implementation Insights (July 13). https://i2insights.org/2021/0713/natural-and-human-sciences-alliance/.

Mariotti, S. (2022a). The economics-engineering nexus: Response to the commentaries. Journal of *Industrial and Business Economics*, 49(1), 1–29. https://doi.org/10.1007/s40812-021-00203-z

Mariotti, S. (2022b). Institutionalizing a pluralistic alliance between economics and engineering. *Inzinerine Ekonomika-Engineering Economics*, 2022, 33(4), 341–355. https://doi.org/10.5755/j01.ee.33.4.31806

Martis, R., Al-Othman, A., Alkasrawi, M., & Tawalbeh, M. (2021). Fuel cells for carbon capture and power generation: Simulation studies. *International Journal of Hydrogen Energy*, 46(8), 6139–6149. https://doi.org/10.1016/j.ijhydene.2020.10.208

Mellit, A., & Kalogirou, S. A. (2008). Artificial intelligence techniques for photovoltaic applications: A review. *Progress in energy and combustion science*, 34(5), 574–632. https://doi.org/10.1016/j.pecs.2008.01.001

Mellit, A., Kalogirou, S. A., Hontoria, L., & Shaari, S. (2009). Artificial intelligence techniques for sizing photovoltaic systems: A review. *Renewable and Sustainable Energy Reviews*, 13(2), 406–419. https://doi.org/10.1016/ j.rser.2008.01.006

Michalski, R. S. (2000). Learnable evolution model: Evolutionary processes guided by machine learning. *Machine learning*, 38(1), 9–40. https://doi.org/10.1023/A:1007677805582

Moore, J. (2017). Thermal hydrogen: An emissions free hydrocarbon economy. International Journal of *Hydrogen Energy*, 42(17), 12047–12063. https://doi.org/10.1016/j.ijhydene.2017.03.182

Nilsson, L. J., Bauer, F., Åhman, M., Andersson, F. N. G., Bataille, C., du Can, SD, S., ... & Vogl, V. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. *Climate Policy*, 21(8), 1053–1065. https://doi.org/10.1080/14693062.2021.1957665

Ortloff, C. R. (2023). CFD investigations of water supply and distribution systems of ancient old and new world archaeological sites to recover ancient water engineering technologies. *Water*, 15(7), 1363. https://doi.org/10.3390/w15071363

Pinto, C. A., McShane, M. K., & Pathak, A. S. (2011). Delayed-bang approach towards more sustainable critical infrastructure risk management. *Journal of Homeland Security and Emergency Management*, 8(1). https://doi.org/10.2202/1547-7355.1533

Plouff, C., & Barakat, N. (2012). Infusion of ABET-Specified professional and academic content into off-campus work experiences via distance learning modules. *Frontiers in Education Conference* Proceedings. https://doi.org/10.1109/FIE.2012.6462309

Qian, Y., Xu, Z. S., Gou, X. J., & Skare, M. (2023a). A survey on energy justice: A critical review of the literature. *Economic Research-Ekonomska Istrazivanja*, 36(3), 2155860. https://doi.org/10.1080/1331677X.2022.2155860

Qian, Y., Xu, Z. S., Qin, Y., Gou, X. J., & Skare, M. (2023b). Measuring the varying relationships between sustainable development and oil booms in different contexts: An empirical study. *Resources Policy*, 85, 103908. https://doi.org/10.1016/j.resourpol.2023.103908

Ramasubbu, N., & Kemerer, C. F. (2019). Integrating technical debt management and software quality management processes: A normative framework and field tests. *IEEE Transactions on Software Engineering*, 45(3), 285–300. https://doi.org/10.1109/TSE.2017.2774832

Rane, V., & MacKenzie, C. A. (2020). Evaluating students with online testing modules in engineering economics: A comparision of student performance with online testing and with traditional assessments. *The Engineering Economist*, 65(3), 213–235. https://doi.org/10.1080/0013791X.2020.1784336

Riggs, J. L. (1977) Engineering economics. McGraw-Hill Book Company.

Riotto, T., Cao, G., Luyben, W. L., & Baltrusaitis, J. (2021). Atmospheric pressure DBD plasma ammonia synthesis and separation process design and environmental impact assessment. *ACS Sustainable Chemistry & Engineering*, 9(39), 13233–13244. https://doi.org/10.1021/acssuschemeng.1c04031

Sanchez-Segura, M. I., Dugarte-Peña, G. L., Amescua-Seco, A., & Medina-Dominguez, F. (2021). Exploring how the intangible side of an organization impacts its business model. *Kybernetes*. https://doi.org/10.1108/K-05-2020-0302

Sarfaraz, A. R. (2006) Project evaluation using Monte Carlo simulation technique. *4th International Industrial Simulation Conference* 2006, 199–201.

Shen, Y., Zhu, H. H., Chen, X. H., & Feng, S. Z. (2012). Low-carbon effect analysis based on the establishment of tunnel portal greening-design. Proceedings of the 13th World Conference of ACUUS: *Advances in Underground Space Development*, ACUUS 2012. https://doi.org/10.3850/978-981-07-3757-3_RP-118-8076

Si, S., Hall, J., Suddaby, R., Ahlstrom, D., & Wei, J. (2023). Technology, entrepreneurship, innovation and social change in digital economics. *Technovation*, 119, 102484. https://doi.org/10.1016/j.technovation.2022.102484

Sonabend, R., Kiraly, F. J., Bender, A., Bischl, B., & Lang, M. (2021). mlr3proba: An R package for machine learning in survival analysis. *Bioinformatics*, 37(17), 2789–2791. https://doi.org/10.1093/bioinformatics/btab039

Su, H. C., & Colander, D. (2021). The economist as scientist, engineer, or plumber? Journal of the History of Economic *Thought*, 43(2), 297–312. https://doi.org/10.1017/S1053837220000231

Su, Y., & Lucko, G. (2015). Synthetic cash flow model with singularity functions. I: Theory for periodic phenomena and time value of money. *Journal of Construction Engineering and Management*, 141(3). https://doi.org/10.1061/ (ASCE) CO.1943-7862.0000938

Sullivan, W. G. (1991). A new paradigm for engineering economy. *The Engineering Economist*, 36(3), 187–200. https://doi.org/10.1080/00137919108903044

Tansey, B., & Stroulia, E. (2010). Valuing software service development in support of business-to-consumer services. *Canadian Journal of Administrative Sciences/Revue Canadienne des Sciences de l'Administration*, 27(1), 39–52. https://doi.org/10.1002/cjas.130

Tsatsaronis, G. (1993). Thermoeconomic analysis and optimization of energy systems. *Progress in energy and combustion science*, 19(3), 227–257. https://doi.org/10.1016/0360-1285(93)90016-8

Ventura-Molina, E., Lopez-Martín, C., Lopez-Yanez, I., & Yanez-Marquez, C. (2020). A novel data analytics method for predicting the delivery speed of software enhancement projects. *Mathematics*, 8(11), 2002. https://doi.org/10.3390/math8112002

Voncina, L., Strizrep, T., Godman, B., Bennie, M., Bishop, I., Campbell, S., ... & Gustafsson, L. L. (2011). Influence of demand-side measures to enhance renin-angiotensin prescribing efficiency in Europe: Implications for the future. *Expert review of pharmacoeconomics & outcomes research*, 11(4), 469–479. https://doi.org/10.1586/erp.11.42

Walwyn, D. R., & Combrinck, C. (2021). Epistemic justice during a global pandemic: Transforming curricula and pedagogical practices to improve student experiences of innovation studies. *Industry and Higher Education*. https://doi.org/10.1177/0950422220987088

Wang, Y., Zhuang, J., Zhou, G., & Wang, S. (2023). Research on unbalanced mining of highway project key data based on knowledge graph and cloud model. *Alexandria Engineering Journal*, 68, 67–81. https://doi.org/10.1016/j.aej.2023.01.010

Wellington, A. M. (1887). The economic theory of the location of railways: An analysis of the conditions controlling the laying out of railways in effect this most judicious expenditure of capital. John. Wiley & sons.

Wu, L. S., Wu, H. F., Zhu, P. H., & Hua, C. C. (2010). Research on ecology landscape water system construction. *Proceedings of the First International Conference on Sustainable Urbanization* (ICSU 2010), 1779–1784.

Xu, H., Li, H., Yao, D., Zhang, X., & Jin, S. (2020). Bi-level optimal planning model of power flow router based on convex relaxation optimisation and sensitivity analysis method. *IET Generation, Transmission & Distribution*, 14(10), 1912–1921. https://doi.org/10.1049/iet-gtd.2019.0356

Xu, X. R., Gou, X. J., Zhang, W. K., Zhao, Y. Y., & Xu, Z. S. (2023). A bibliometric analysis of carbon neutrality: Research hotspots and future directions. *Heliyon*, 9(8), e18763. https://doi.org/10.1016/j.heliyon.2023.e18763

Yilmaz, M., & O'Connor, R. V. (2011). An approach for improving the social aspects of the software development process by using a game theoretic perspective: *Towards a theory of social productivity of software development teams. scitepress.* https://doi.org/10.5220/0003492900350040

Young, D., Scharp, R., & Cabezas, H. (2000). The waste reduction (WAR) algorithm: Environmental impacts, energy consumption, and engineering economics. *Waste manage*ment, 20(8), 605–615. https://doi.org/10.1016/S0956-053X(00)00047-7

Youns, Y. T., Manshad, A. K., & Ali, J. A. (2023). Sustainable aspects behind the application of nanotechnology in CO2 sequestration. *Fuel*, 349, 128680. https://doi.org/10.1016/j.fuel.2023.128680

Zhang, W., Li, X., & Zhang, J. (2020). Economic prediction method of port and ocean engineering based on grey theory. *Journal of Coastal Research*, 103, 125–128. https://doi.org/10.2112/SI103-026.1

Zhang, Y., Wang, W., Wang, Z., Gao, M., Zhu, L., & Song, J. (2021). Green building design based on solar energy utilization: Take a kindergarten competition design as an example. *Energy Reports*, 7, 1297–1307. https://doi.org/10.1016/j.egyr.2021.09.134

Zhu, X. L., & Zhao, C. (2013). Investigation of the roadside forest based on "Carbon Neutral". *Advanced Materials Research*, 779, 1314–1319. https://doi.org/10.4028/www.scientific.net/AMR.779-780.1314

## Authors' Biographies

**Yu Qian** received the B. S. degree from Chongqing Jiaotong University, China, in 2019. She is currently pursuingthemaster's degree from Sichuan University. Her research interests include energy justice, supply chain, and multi-attributedecision making, data mining.

**Xujie Gou** received the dual Ph.D. degrees in management science and engineering fromSichuan University, Chengdu, China, in 2019, and in information and communication technology from the University of Granada, Granada, Spain in 2019. He is currently an Associate Research Professor with the Business School, Sichuan University. Hehaspublished more than 50 peer reviewed papers including IEEE Transactions on Cybernetics, Knowledge-BasedSystems, Information Sciences. His current research interests include large-scale group decision making, double hierarchylinguisticterm set, and computing with words.

**Zeshui Xu** received the Ph.D. degree in management science and engineering from Southeast University, China, in2003. He has been selected as a Thomson Reuters Highly Cited Researcher include in The World's Most Influential Mindsfrom 2014 to 2018, and the Most Cited Chinese Researcher (ranked first in Computer Science from2014 to 2018, releasedby Elsevier). His H-index is 114. He has contributed more than 550 articles to professional journals and Conferences. Hisresearch interests include information fusion, group decision making, computing with words, and aggregation operators.

The article has been reviewed.

Received in November 2022; accepted in January 2024.