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A Study on the Characteristics of Academic Topics Related to Renewable Energy Using the Structural Topic Modeling and the Weak Signal Concept

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Abstract: It is important to examine in detail how the distribution of academic research topics related to renewable energy is structured and which topics are likely to receive new attention in the future in order for scientists to contribute to the development of renewable energy. This study uses an advanced probabilistic topic modeling to statistically examine the temporal changes of renewable energy topics by using academic abstracts from 2010–2019 and explores the properties of the topics from the perspective of future signs such as weak signals. As a result, in strong signals, methods for optimally integrating renewable energy into the power grid are paid great attention. In weak signals, interest in large-capacity energy storage systems such as hydrogen, supercapacitors, and compressed air energy storage showed a high rate of increase. In not-strong-but-well-known signals, comprehensive topics have been included, such as renewable energy potential, barriers, and policies. The approach of this study is applicable not only to renewable energy but also to other subjects.

Keywords: renewable energy; structural topic modeling; weak signal; future sign

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1. Introduction

Renewable energy is an area that is growing faster than any other sector along with energy transition trends. According to the IEA (International Energy Agency) [1], renewables supply in OECD (Organisation for Economic Cooperation and Development) countries showed an increase in average annual growth rate of 0.9% (1990 to 2000), 3.0% (2000 to 2010), and 3.3% (2010 to 2019), in which the growth of renewable energy has been accelerating recently. Along with the expansion of renewable energy, there are various issues of interest. The issues span many fields, including economy, environment, politics, and technology. The scientific community is contributing to the promotion of the spread of renewable energy by finding the fundamental reasons for the issues and suggesting solutions to related problems. Therefore, it is important t to examine in detail how the distribution of academic research topics related to renewable energy is structured and which topics are likely to receive new attention in the future in order for scientists to contribute to the development of renewable energy.

Academic research on topics of renewable energy has been conducted continuously in recent years [2–5]. However, they have weak features in terms of statistical verification of changes in renewable energy topics. Thus, a more rigorous analysis of the change in renewable energy topics is additionally required, and it is necessary to increase understanding of the topics by examining the properties of the derived topics beyond deriving them.

This study uses an advanced probabilistic topic modeling to statistically examine the temporal changes of renewable energy topics, and explores the properties of topics from the perspective of future signs such as weak signals. The main research questions in this study are as follows.

1. What are the academic topics that the scientific community is paying attention to concerning renewable energy?

2. What academic topics have increased or decreased statistically over the last 10 years (2010–2019)?
3. Among the many academic topics, which ones are receiving strong interest? What are the topics that are still low in interest, but are growing rapidly? What are the topics that still attract high interest, but have recently gained less interest?

This study not only derives recent key topics of renewable energy and provides information to understand topic changes over time, but also introduces a way to understand more intuitively changes in renewable energy-related topics by combining the concept of weak signals with probabilistic topic modeling.

The structure of this study is as follows. Section 1 is the introduction, Section 2 examines issues related to renewable energy through a literature review. Section 3 presents methods of this study, and Section 4 describes renewable energy topics derived through the methods of this study. Section 5 additionally examines the meaning of key topics. Section 6 concludes by examining the contributions and limitations of this study.

2. Literature Review

Renewable energy is the latest and fastest growing energy source among various energy sources and is creating various issues in many areas. This section reviews issues related to renewable energy through the existing literatures.

The topics of the literature dealing with the policy issues of renewable energy include regulation [6–8], feed-in tariffs (FiT) [9–11], and an increase in the acceptance of renewable energy [12–14].

The research on policy covers potential effects of renewable energy policy and regulatory law frameworks [6,7]. Byrnes et al. [8] stated that effective policies and regulatory frameworks are the most important factors for encouraging renewable energy diffusion.

In addition to the topic of the regulatory framework, there has been a large amount of research covering FiT in the policy field. FiT is used by many countries, including developing countries, as a mechanism to promote renewable energy development. The research on FiT covers the effectiveness, drivers, and challenges of the FiT policy [9]. Ndiritu and Engola [9] found that the main challenges of FiT policy are related to the unavailability of technical expertise for policy design and inefficiency of policy implementation. There was also research comparing two types of support mechanisms. One was a study comparing FiT and tradable green certificates (TGC) [10], and the other was a study comparing FiT and the renewable portfolio standards (RPS) [11].

Along with the other issues mentioned earlier, the issue of acceptance has recently been emphasized. This is because the acceptance of renewable energy is an essential factor in the spread and development of renewable energy. The research on acceptance covers factors affecting the acceptance of renewable energy technologies [12,13] and ways that government policies on renewable energy can induce more public support and participation [14].

The topics of literature dealing with the economic issues of renewable energy mainly include economic evaluation [15–17] and the levelized cost of energy (LCOE) [18–20].

The research on economic evaluation covers a topic such as economic analysis of adding renewable energy generators to increase the proportion of renewable energy [15]. Asrari et al. [15] found that adding renewable power generators both before and after the expansion of the grid could result in more economical power systems. Zhou et al. [16] researched the reliability and economic evaluation of power systems using renewable energy and found that the types and sizes of renewable energy generation have a significant impact on system reliability and economic feasibility. Liu et al. [17] pointed out the difficulty of quantifying assessment indicators for technology–economy evaluation of renewable energy resources, and developed a computational methodology that quantifies technology–economy indicators, including power generation, economic costs, income, and carbon emissions.

The research on LCOE covers topics such as developing a new cost model for assessing the LCOE of renewable energy sources in accordance with the Power Purchase Agreement (PPA) contract [18] and the effect of input data's uncertainty on LCOE values [19]. Tran and Smith [19] indicated that emerging renewable energy technologies are exposed to high uncertainties in both technology and economic performance. Aldersey-Williams et al. [20] stated that LCOE estimates are based on unreliable public domain data. In other words, audited accounting data from renewable energy generators' special purpose vehicle (SPV) companies were more reliable sources than information provided by renewable energy generator developers in the public domain. This is because public domain data, which are not subject to audit or investigation by tax authorities, are more likely to be distorted than audited accounting data. Aldersey-Williams et al. [20] also proposed a methodology to determine more accurate LCOE estimates using the audited data.

The topics of literature dealing with the technical issues of renewable energy mainly include energy storage [21,22] and microgrids [23–25].

The main constraints for increasing the spread of renewable energy are availability and intermittency. This problem can be solved by storing energy. Renewable energy can be combined with an energy storage system (ESS) to provide stable and continuous power supply, which is a key factor in the development of renewable energy. The research on energy storage covers the economic aspects of various storage technologies [21] and characteristics of batteries required for the storage of electricity from renewable energy sources [22].

Microgrids are self-sufficient power grids based on a small and independently distributed power source, which enables stable supply and demand of power along with ESS and allows the sale of surplus power in conjunction with the existing power system. The research on microgrids covers the assessment of reliability, economic and environmental benefits of renewable energy resources in microgrid systems [23], and the real-time energy management for a single microgrid system that organizes renewable power generation systems and energy storage systems [24]. Badal et al. [25] stated that renewable energy sources act as the main drivers of the microgrids.

Studies covering renewable energy issues comprehensively used a variety of methods. Examples include studies using interviews [6,9], surveys [7,12,13], and reviews [26,27]. Jurasz et al. [26] presented a comprehensive review of existing publications, and Sinsel et al. [27] used root cause analysis and semi-structured interviews. Jurasz et al. [26] analyzed the existing literature that evaluates the complementarity between renewable energy sources, comparing and summarizing existing theories and models. Sinsel et al. [27] studied the solution technologies that can be used to integrate variable renewable energy sources into the modern power system.

In addition, Yan et al. [28], Van Eck and Waltman [29], Alcayde et al. [30], Gan et al. [31], and Azevedo et al. [32] conducted research based on bibliographic data. Yan et al. [28], Van Eck and Waltman [29], and Alcayde et al. [30] tried community detection in networks, and Gan et al. [31] and Azevedo et al. [32] tried keywords analysis. Alcayde et al. [30] analyzed publications of renewable energy, including "renewable energy" in the title or keyword. Gan et al. [31] summarized the research on the supply and demand relationship of the renewable energy power system, using a total of 473 studies published in academic journals. Azevedo et al. [32] analyzed the relationship between supply chain performance and renewable energy.

In order to comprehensively and efficiently analyze vast topics related to renewable energy, research is actively conducted using topic modeling. Shin et al. [2] collected media articles related to renewable energy in Korean from 2006 to 2015 to analyze the trend of renewable energy in South Korea. Additionally, latent dirichlet allocation (LDA), which is a probabilistic topic modeling, was used to extract a total of 20 renewable energy topics. According to research by Shin et al. [2], five out of twenty topics on the rise due to continued interest are the smart grid business, solar energy supply business, RPS, energy-saving education programs in the power sector, and the free trade agreement (FTA). Jiang et al. [3]

collected 1726 scientific papers on hydropower from 1994 to 2013 and analyzed 29 topics. Jiang et al. [3] attempted a bibliometric analysis based on LDA. According to Jiang et al. [3], in hydropower research, topics which are related to environmental, ecologic, or sustainable issues such as fish, species, climate, emission, lake, sediment, and Turkey (a main country that prioritizes hydropower development) are hotspots. Bickel [4] collected 26,533 Scopus-indexed abstracts published from 1990 to 2016 and analyzed 300 topics by using LDA. According to research by Bickel [4], energy storage, photonic materials, nanomaterials, and biofuels are among the topics with the strongest trends. Xu et al. [5] collected 3743 scientific papers from 1992 to 2018 and researched renewable energy fields of electrical and electronic disciplines. They also used LDA and analyzed a total of 29 topics. According to research by Xu et al. [5], microgrids, smart grids, electric vehicles, network communication technology, and power system stability are hot topics.

3. Materials and Methods

This study has collected the abstracts of academic papers containing the keyword "renewable energy" in the titles, abstracts, and keywords of papers over the last 10 years (2010 to 2019) from ScienceDirect.com, an academic database. As a result of the collection, 26,421 abstracts of papers were collected.

ScienceDirect is a website that serves as a pathway to a large bibliographic database of scientific publications of the British publisher Elsevier. ScienceDirect provides access to more than 4000 academic journals [33]. However, Web of Science and Scopus are known to have about five times more accessible scientific abstracts than ScienceDirect. The advantage of using Web of Science or Scopus is that more studies can be reviewed. The reason why Web of Science or Scopus could not be used in this study was due to the limitation of access rights. However, ScienceDirect is also evaluated as one of the academic search systems suitable for evidence synthesis in the form of systematic reviews and can be used as a principal search system [34]. Therefore, when this study uses ScienceDirect, it is possible to sufficiently synthesize multidisciplinary research trends related to renewable energy.

The reason for selecting "renewable energy" as a keyword is to search for more relevant literature on renewable energy. Keywords similar to renewable energy include sustainable energy, alternative energy, and clean energy. However, these similar keywords may include not only renewable energy, but other issues such as energy systems, nuclear power, and cleaner fossil fuels. In addition, detailed energy sources such as solar energy, wind energy, and geothermal energy may be used as search keywords. However, when this detailed keyword related to renewable energy sources is used, topic analysis results can be centered on renewable energy sources with high proportions such as solar or wind. In this study, since the search keyword "renewable energy" alone can provide a sufficient amount of academic abstracts for probabilistic topic analysis, it is determined that there is no problem in grasping the academic interests of researchers on renewable energy.

This study analyzes the change of topics related to renewable energy using a probabilistic topic modeling method which is an unsupervised classification of documents. The method has the advantage of being able to easily identify research topics by finding latent topics hidden in the contents of the documents. Probabilistic topic modeling is known to have better accuracy than the established topic modeling that uses a linear algebra of singular value decomposition (SVD) [35]. In addition, the method using SVD has difficulty in deriving the optimal number of dimensions [36].

Looking at existing studies using probabilistic topic modeling, LDA is generally used in analyzing renewable energy topics and trends. LDA is one of the most common algorithms for topic modeling. LDA has the premise that all documents are composed of topics, and all topics are a mixture of words. LDA searches for a mixture of topics that describe each document, and searches for a mixture of words associated with each topic [37]. The main goal of LDA is to find topics potentially contained in a document based on the words it contains. Existing studies have found potential topics included in renewable energy-related literatures through LDA, interpreted their meaning, and drew implications.

However, to look at the trend of renewable energy, a variable of time should be considered. LDA focuses on point estimates of word or topic probabilities without confidence intervals, making it difficult to perform statistical hypothesis testing of document covariates [38]. To overcome these limitations of LDA, Robert et al. [39] proposed structural topic modeling (STM).

STM allows for observed covariates, such as document source and time of document release, to affect two components of the model, which are topic prevalence and topical content. Topic prevalence refers to the proportion of a document devoted to a topic and topical content refers to the word rates used in discussing a topic. In STM, topical prevalence and topical content are specified as a simple generalized linear model on an arbitrary number of document-level covariates, enabling researchers to introduce experimental design elements that informed document collection into the model [40]. Therefore, this study can check whether topics related to renewable energy changed statistically significantly in the second half of the 2010s compared to the first half of the 2010s by using an observed covariate of the paper publication year through STM.

Furthermore, by utilizing a weak signal concept, this study look at which topics are still low in interest but have the potential for further development. It also looks at a strong signal with a positive increasing rate of interest and a not-strong-but-well-known (NSWK) signal with a high interest but a negative increasing rate. The concept of the weak signal was first used by Ansoff [41] as a concept that contrasts with the strong signal. He points out that when a company establishes its future strategy, it can face a crisis from unexpected changes if it establishes a strategy that responds only to strong signals. Holopainen and Toivonen [42] indicated that Ansoff [41] defined the weak signal as indications of possible change in the future and emphasized that it was necessary to use it as a warning of a new danger or a signal indicating a new possibility. Based on the concept of weak signals, Yoon [43] extracted weak and strong signals by considering the frequency of words, documents, and the increasing rate of the frequency using text mining. Furthermore, Park and Kim [44] and Park and Cho [45] presented additional NSWK signals and latent signals.

Figure 1 below shows the existing method of searching for future signs using text mining. The keyword emergence map (KEM) is based on term frequency (TF), and the keyword issue map (KIM) is based on document frequency (DF). Additionally, the signals extracted from KEM and KIM are presented as future signs.

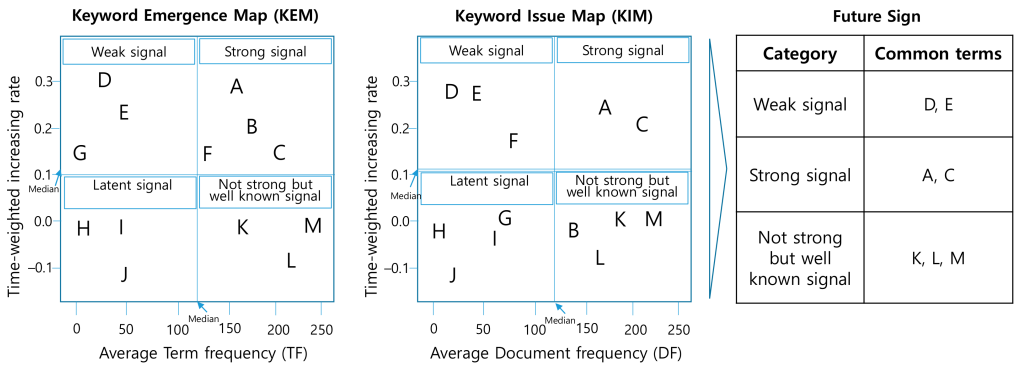

Figure 1. Existing process identifying future signs by using text mining [44,45].

The time-weighted increasing rate consists of the degree of visibility (DoV) and the degree of diffusion (DoD). *DoV* is reflected in the KEM as a proxy of visibility and *DoD* is in the KIM as a proxy of diffusion. The indices are calculated, respectively, by the following equations.

$$DoV_{ij} = \left(\frac{TF_{ij}}{NN_j}\right) \times \{1 - tw \times (n - j)\} \quad (1)$$

$$DoD_{ij} = \left(\frac{DF_{ij}}{NN_j}\right) \times \{1 - tw \times (n - j)\} \quad (2)$$

where, NN is the total number of documents, tw is time weight, n is an entire time period, j is a point of time. The above DoV and DoD are the variables that are obtained, respectively, with the TF and the DF divided by the total number of documents to calculate the rate at a certain point of time [45]. Yoon [43] applied 0.05 for tw to his own research on solar cells. The most recent year has zero for $(n - j)$ and $\{1 - tw \times (n - j)\}$ results in 1. The time weight tw is not empirically verified and can be applied differently according to authors.

This method is being used in various fields such as Kim et al. [46], Krigsholm and Riekkinen [47], Park and Cho [48], and Roh and Choi [49]. However, it has two big limitations. First, signals that are not included in KEM and KIM are ultimately not included in future signs. As shown in Figure 1, in KEM, weak signals include D, E, and G, and in KIM, D, E, and F are included, but only D and E are included in the final future signs. Therefore, there is a problem in that G and F are omitted. Second, since the signals extracted as future signs are in the form of words, it is difficult to interpret their meaning. Therefore, Park and Cho [48] proposed a method of extracting documents similar to each keyword in order to facilitate interpretation of the meaning of keywords selected as future signs.

In this study, to overcome the limitations of the existing technique of searching for future signs using text mining, topic proportions are used instead of the frequency of words and documents. As shown in Figure 2, the topic proportion extracted through the STM instead of the average TF and the average DF is set on the x-axis, and the increasing rate of the topic proportion instead of increasing rates based on TF and DF is set on the y-axis. This approach can solve the problem of omitting some keywords by replacing the frequency of words and documents with topic proportions. In addition, since one topic is composed of several keywords, it becomes easier to interpret the meaning of future signals.

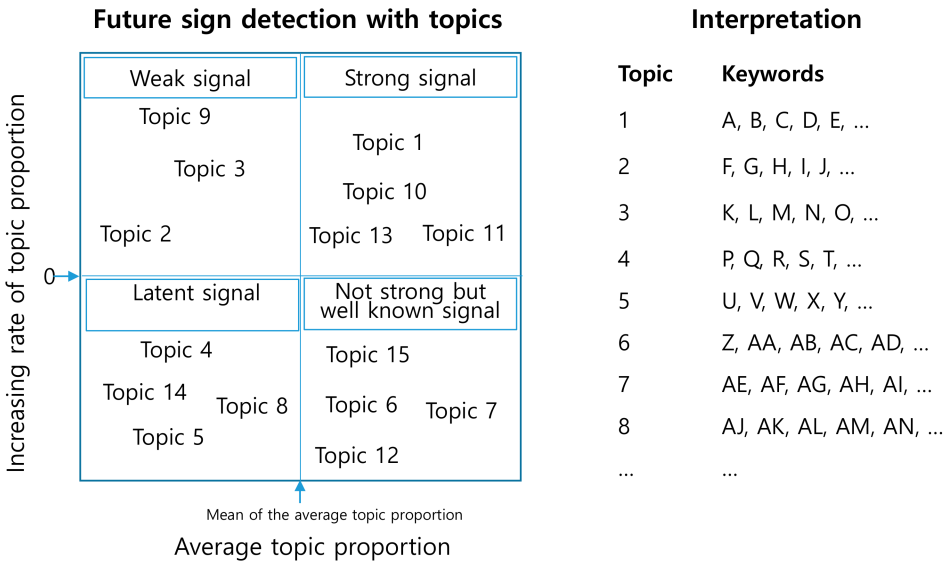

Figure 2. New process identifying future signs by using structural topic modeling (STM).

This study carried out STM using the R package called "stm" and used a function called "search" provided in the stm package to find the appropriate number of topics. The stm package extracts a user-determined number of topics but provides indices such as held out likelihood [50] and residuals [51] to determine the appropriate number of topics based on the data.

4. Results

This study collected academic abstracts related to renewable energy for a period of 10 years from 2010 to 2019. The number of documents collected in the first half of the 2010s was 7952, and in the second half of the decade 18,469.

Table 1 shows the frequency and share of terms related to renewable energy sources. On a TF basis, TF for solar and wind energy accounts for about 4/5 of the total TF of renewable energy sources, accounting for the majority. The share of solar energy is about 47% and wind power is about 37%. Bioenergy is about 7%, geothermal is about 4%, and 5% accounts for others. In terms of the increase rate of TF in the second half of the 2010s compared to the first half of the decade, geothermal and solar energy increased by about 140%, followed by wind power (about 88%).

Table 1. Term frequency (TF) by renewable energy type.

Period, %	Terms						
	Solar	**Wind**	**Bio**	**Geothermal**	**Tidal**	**Hydro**	**Total**
2010–2014	5550	5118	4118	483	363	333	15,965
2015–2019	13,170	9634	6576	1170	585	606	31,741
2010–2019	18,720	14,752	2883	1653	948	939	39,895
Share (%)	46.9	37.0	7.2	4.1	2.4	2.4	100
Increase Rate (%)	137.3	88.2	59.7	142.2	61.2	82.0	98.8

Table 2 below shows the frequency and share of the top 10 countries by TF. According to TF of country names based on the United Nations (UN) list, China appears to have the highest proportion. Compared to India in the second place, the frequency of China was more than double. After China and India, Turkey, Malaysia, Germany, the United States, Brazil, Spain, Iran, and Italy followed. The total TF of these 10 countries accounted for about half of that of all countries. The overall increase rate was more than 50% in the second half compared to the first half of the 2010s excluding Germany and the United States.

Table 2. Term frequency (TF) by country.

Period, %	Terms									
	China	**India**	**Turkey**	**Malaysia**	**Germany**	**US**	**Brazil**	**Spain**	**Iran**	**Italy**
2010–2014	783	333	309	483	257	232	185	172	159	150
2015–2019	1383	580	548	1170	330	329	319	313	259	257
2010–2019	2166	913	857	673	587	561	504	485	418	407
Share (%)	13.4	5.7	5.3	4.2	3.6	3.5	3.1	3.0	2.6	2.5
Increase Rate (%)	76.6	74.2	77.3	51.1	28.4	41.8	72.4	82.0	62.9	71.3

This study focuses on the proportion and change of topics rather than on TF-based analysis. Therefore, the results are described based on the results of topic analysis. This study looked at held-out likelihood, residuals, semantic coherence, and lower bound to find an appropriate number of topics. It used the document-completion method to obtain the held-out likelihood by using the stm package. The method is similar to cross validation and the estimation of the probability that words appear within a document when those words have been deleted from the document in the estimation step. The residual check is a test for overdispersion of the variance of the multinomial within the STM data generation process. If the residuals are overdispersed, it may be that more topics are needed to absorb some of the extra variance. Semantic coherence is closely relevant to pointwise mutual information and is maximized when the most likely words in a given topic frequently come together. Convergence can be checked by the change in the approximate variational lower bound. Once the boundary has sufficiently small changes between iterations, the model is

considered convergent [52]. The higher the held-out likelihood and semantic coherence, the lower the residuals and lower bound, the better the model performance.

As shown in Figure 3 below, this study first extracted 200 topics and drew diagnostic plots. As a result, it was confirmed that the increasing rate of held-out likelihood slowed at about 120 topics, and the lowest value was shown at about 160 topics in terms of residuals. However, the semantic coherence and lower bound showed a pattern that the coherence and convergence of the model decreased as the number of topics increased. Therefore, it found that there was a trade-off between the indices of held-out likelihood and residuals and the indices of semantic coherence and lower bound. It also considered that as the number of topics derived through STM increases, topics are subdivided and there are more local issues. Considering these results comprehensively, this study finally decided to extract 100 topics.

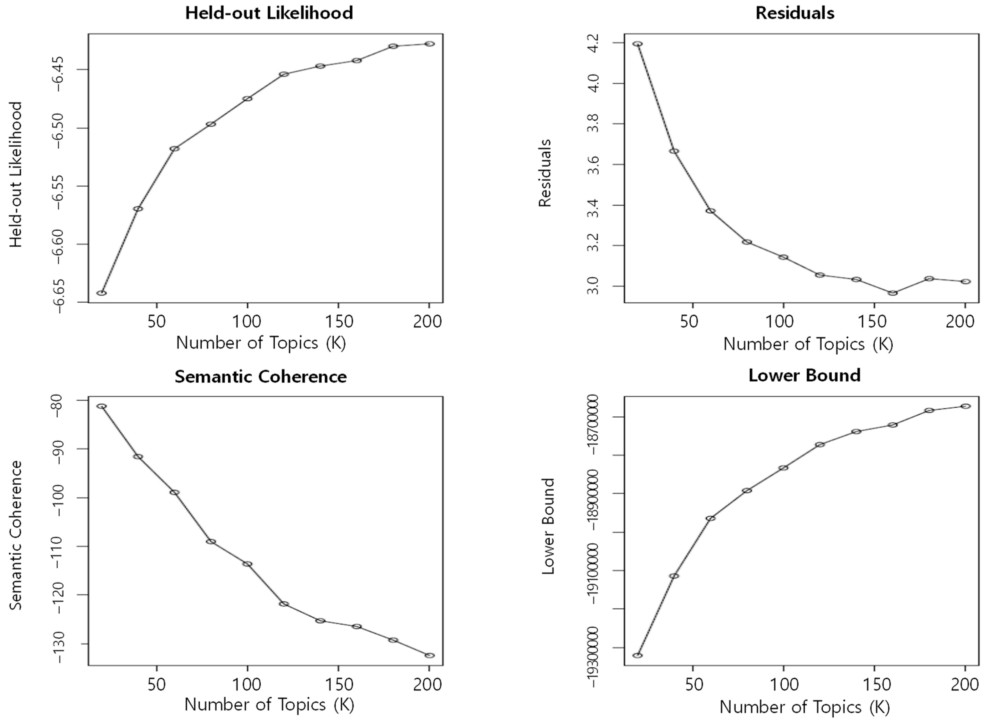

Figure 3. Diagnostic values by number of topics.

A total of 100 topics extracted through STM were arranged in the quadrant as shown in Figure 4 below. The first, second, third, and fourth quadrants mean strong signal, weak signal, latent signal, and NSWK signal, respectively. The division line drawn with a dotted line on the *x*-axis means the mean value of the overall average topic proportion. The dotted line on the *y*-axis is based on 0. If it is greater than 0, it means that the topic proportion has increased in the second half of the 2010s, and if it is less than 0, it means the opposite. This study also examined whether the increasing rate of topic proportion was statistically significant. To present the research results more intensively, it examined the contents focusing on strong signals, weak signals, and NSWK signals.

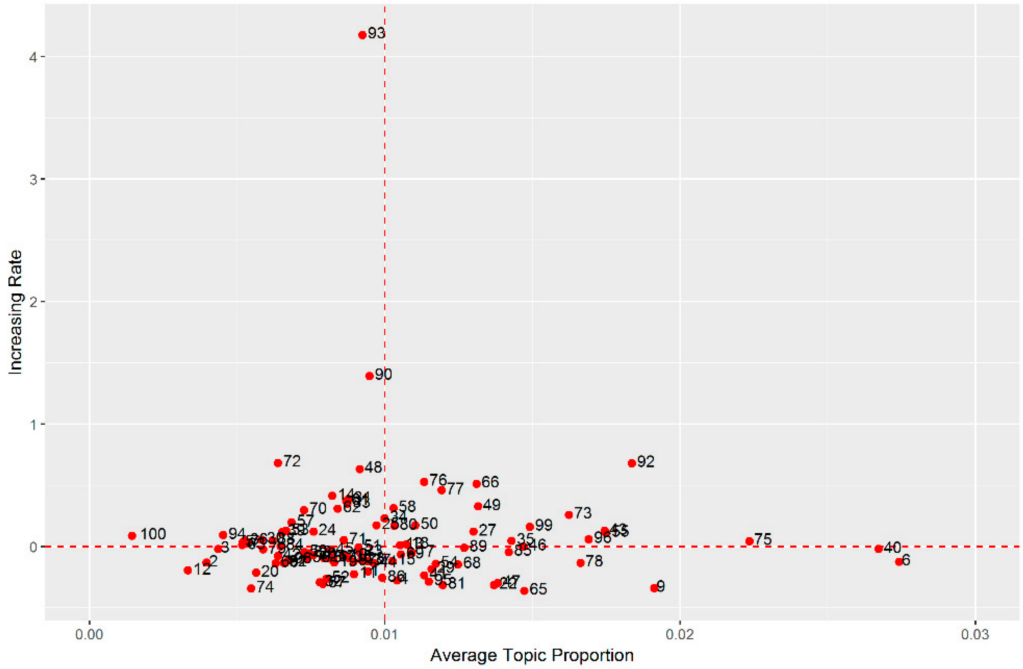

Figure 4. Placement of topics in the quadrant.

4.1. Strong Signals

Table 3 below contains statistics including mean values of the topic proportions, increasing rates, and *p*-values by topic. The keywords are presented after a stemming which is the pre-processing of the data in STM. The keywords are presented in the same form in the rest of this section. As shown in Table 3, strong signals included 18 out of 100 topics. Additionally, in the second half of the 2010s, there were 12 topics whose *p*-values were less than the significance level of 0.05. Among the topics selected for strong signals, focus on the topics with *p*-values lower than the significance level of 0.05 are as follows.

Table 4 shows documents related to topics where the increase in topic proportion is statistically significant. Based on Table 4, the meaning of the main topics is as follows. Topic 43 discusses the relationship between renewable energy and efficiency. Topic 49 deals with the prediction of renewable energy generation, and Topic 50 deals with the effective use of renewable energy heat. Topic 55 deals with hybrid renewable energy systems, and Topic 58 discusses latent heat storage systems. Topic 66 discusses the combination of microgrids and demand response, and Topic 73 deals with the social implications of energy transitions. Topic 76 discusses smart grids that can flexibly connect renewable energy with irregular power generation to the grid. Topic 77 deals with frequency control using energy storage systems or electric vehicles in microgrids. Topic 80 focuses on discussions on maintaining the performance of remote renewable energy facilities such as marine renewable energy and offshore wind power. Topic 92 discusses the algorithm for solving the problem of optimal power flow incorporating renewable energy sources. Topic 99 contains studies examining the relationship between renewable energy consumption and economic growth.

4.2. Weak Signals

As shown in Table 5, a total of 26 out of 100 topics were assigned to weak signals. Additionally, 13 topics had *p*-values of an increasing rate of topic proportion less than the significance level of 0.05. Based on Table 6, this study focuses on topics with a *p*-value lower than the significance level of 0.05 in weak signals.

Table 3. Topics selected as strong signals.

Topics	Keywords						
	Mean	**Inc.**	**Estimate**	**Std. Error**	***t*-Value**	**Pr(>|t|)** [1]	
13	market, price, profit, trade, competit, volatil, reserv, revenu, impact, particip, . . .						
	0.011	0.012	0.000	0.001	0.223	0.823	
18	heat, pump, district, system, thermal, chp, boiler, combin, sourc, effici, . . .						
	0.011	0.015	0.000	0.001	0.216	0.829	
27	voltag, convert, propos, current, invert, sourc, paper, point, maximum, qualiti, . . .						
	0.013	0.122	0.001	0.001	1.561	0.119	
35	build, energi, consumpt, design, hous, effici, residenti, perform, save, improv, . . .						
	0.014	0.045	0.001	0.001	0.630	0.529	
43	increas, higher, rate, effect, result, lower, signific, decreas, level, effici, . . .						
	0.017	0.128	0.002	0.000	4.994	0.000	**
49	predict, forecast, data, method, error, accuraci, propos, estim, time, neural, . . .						
	0.013	0.328	0.004	0.001	3.855	0.000	**
50	effici, cycl, exergi, perform, thermodynam, analysi, pressur, orc, temperatur, . . .						
	0.011	0.175	0.002	0.001	2.051	0.040	*
55	system, hybrid, configur, design, analysi, differ, present, econom, base, combin, . . .						
	0.017	0.110	0.002	0.001	3.525	0.000	**
58	thermal, temperatur, heat, transfer, fluid, experiment, perform, exchang, pcm, . . .						
	0.010	0.311	0.003	0.001	3.209	0.001	**
66	load, demand, manag, microgrid, oper, peak, respons, profil, resourc, time, . . .						
	0.013	0.517	0.005	0.001	7.601	0.000	**
73	transit, framework, toward, social, institut, transform, role, approach, paper, polit, . . .						
	0.016	0. 261	0.004	0.001	4.013	0.000	**
75	approach, evalu, method, analysi, methodolog, tool, assess, propos, differ, criteria, . . .						
	0.022	0.044	0.001	0.001	1.208	0.227	
76	integr, flexibl, smart, provid, servic, benefit, challeng, system, concept, balanc, . . .						
	0.011	0.526	0.005	0.001	8.443	0.000	**
77	control, strategi, frequenc, propos, dynam, regul, stabil, paper, oper, fluctuat, . . .						
	0.012	0.457	0.004	0.001	5.536	0.000	**
80	test, oper, monitor, condit, structur, failur, load, platform, experiment, detect, . . .						
	0.010	0.174	0.002	0.001	2.235	0.025	*
92	optim, propos, problem, algorithm, method, oper, minim, consid, solut, constraint, . . .						
	0.018	0.679	0.009	0.001	9.968	0.000	**
96	model, simul, data, paramet, result, valid, dynam, comput, base, mathemat, . . .						
	0.017	0.061	0.001	0.001	1.920	0.055	
99	consumpt, growth, energi, econom, renew, relationship, effect, period, gdp, panel, . . .						
	0.015	0.161	0.002	0.001	2.060	0.039	*

[1] Significance level: 0.1, * significance level: 0.05, ** significance level: 0.01.

Table 4. Relevant documents with strong signal topics [1].

Topics	Authors (Year)	Titles
43	Croonenbroeck and Huttel (2017)	Quantifying the economic efficiency impact of inaccurate renewable energy price forecasts
	Goldstein (2018)	Renewables may be plunging in price, but efficiency remains the cornerstone of the clean energy economy
	Rahman et al. (2015)	Effects of various parameters on PV-module power and efficiency
49	Alzahrani et al. (2017)	Solar Irradiance Forecasting Using Deep Neural Networks
	Ghofrani et al. (2016)	A novel soft computing framework for solar radiation forecasting
	Paoli et al. (2010)	Forecasting of preprocessed daily solar radiation time series using neural networks
50	Ghosh and Dincer (2014)	Development and analysis of a new integrated solar-wind-geothermal energy system
	Yari et al. (2013)	Thermodynamic analysis and optimization of a novel dual-evaporator system powered by electrical and solar energy sources
	Li (2016)	Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part I: Energy and exergy performance evaluation
55	Panayiotou et al. (2012)	Design and simulation of a PV and a PV-Wind standalone energy system to power a household application
	Sawle et al. (2018)	Socio-techno-economic design of hybrid renewable energy system using optimization techniques
	Rezk and Dousoky (2016)	Technical and economic analysis of different configurations of stand-alone hybrid renewable power systems—A case study
58	Li and Zhang (2018)	Dynamic heat transfer characteristics of wall implanted with heat pipes in summer
	Wang et al. (2019)	Experimental and modeling study on thermal performance of hydrated salt latent heat thermal energy storage system
	Joybari et al. (2019)	Experimental investigation of multiple tube heat transfer enhancement in a vertical cylindrical latent heat thermal energy storage system
66	Zakariazadeh et al. (2014)	Smart microgrid energy and reserve scheduling with demand response using stochastic optimization
	Sattarpour et al. (2016)	A multi-objective HEM strategy for smart home energy scheduling: A collaborative approach to support microgrid operation
	Hakimi and Tafreshi (2016)	Smart virtual energy storage control strategy to cope with uncertainties and increase renewable energy penetration
73	Faller (2016)	A practice approach to study the spatial dimensions of the energy transition
	Stirling (2014)	Transforming power: Social science and the politics of energy choices
	Dóci (2015)	Exploring the transition potential of renewable energy communities
76	Al-Ali (2016)	Internet of Things Role in the Renewable Energy Resources
	Lund et al. (2017)	Smart energy and smart energy systems
	Mathiesen et al. (2015)	Smart Energy Systems for coherent 100% renewable energy and transport solutions
77	Yan et al. (2016)	Frequency Control Strategy of Hybrid Energy Storage System for Microgrid Based on Frequency Hysteretic Loop
	Babaiahgari et al. (2019)	Coordinated control and dynamic optimization in DC microgrid systems
	Li et al. (2019)	A frequency control strategy of electric vehicles in microgrid using virtual synchronous generator control
80	Thies et al. (2016)	Accelerated reliability testing of articulated cable bend restrictor for offshore wind applications
	Peeters et al. (2018)	Vibration-based bearing fault detection for operations and maintenance cost reduction in wind energy
	Luxmoore et al. (2016)	Analytical performance assessment of a novel active mooring system for load reduction in marine energy converters
92	Elattar and ElSayed (2019)	Modified JAYA algorithm for optimal power flow incorporating renewable energy sources considering the cost, emission, power loss and voltage profile improvement
	Basu (2019)	Squirrel search algorithm for multi-region combined heat and power economic dispatch incorporating renewable energy sources
	Niknam (2012)	Distribution feeder reconfiguration considering fuel cell/wind/photovoltaic power plants
99	Tugcu and Topcu (2018)	Total, renewable and non-renewable energy consumption and economic growth: Revisiting the issue with an asymmetric point of view
	Dogan (2016)	Analyzing the linkage between renewable and non-renewable energy consumption and economic growth by considering structural break in time-series data
	Ito (2017)	CO_2 emissions, renewable and non-renewable energy consumption, and economic growth: Evidence from panel data for developing countries

[1] Only relevant documents for topics with a *p*-value of 0.05 or less are presented.

Table 5. Topics selected as weak signals.

Topics	Keywords						
	Mean	**Inc.**	**Estimate**	**Std. Error**	**t-Value**	**Pr(>|t|)** [1]	
5	urban, citi, area, provinc, zone, western, map, popul, saudi, rooftop, . . .						
	0.005	0.035	0.000	0.000	0.436	0.663	
7	stakehold, tempor, group, rule, identifi, expert, within, i nform, key, permit, . . .						
	0.005	0.030	0.000	0.000	0.376	0.707	
14	storag, energi, store, intermitt, capac, air, ess, compress, tank, larg, . . .						
	0.008	0.415	0.003	0.000	5.721	0.000	**
24	methan, reactor, remov, product, anaerob, oper, yield, studi, concentr, microbi, . . .						
	0.008	0.126	0.001	0.001	1.230	0.219	
25	plan, uncertainti, risk, decis, expans, stochast, can, robust, uncertain, portfolio, . . .						
	0.010	0.175	0.002	0.001	3.053	0.002	**
30	geotherm, ground, mine, reservoir, well, underground, extract, depth, rock, use, . . .						
	0.006	0.059	0.000	0.001	0.494	0.621	
31	reaction, catalyst, oxid, metal, catalyt, convers, high, activ, select, format, . . .						
	0.009	0.392	0.003	0.001	3.556	0.000	**
33	distribut, network, communic, resource, loss, decentr, manage, der, architectur, . . .						
	0.009	0.348	0.003	0.001	4.653	0.000	**
34	grid, penetr, transmiss, connect, system, line, power, interconnect, high, oper, . . .						
	0.010	0.231	0.002	0.001	3.604	0.000	**
36	size, scale, mix, particl, larg, larger, smaller, time, differ, effect, . . .						
	0.005	0.048	0.000	0.000	0.805	0.421	
39	membran, pressur, densiti, solut, feed, concentr, pro, revers, salin, perform, . . .						
	0.007	0.118	0.001	0.001	1.074	0.283	
48	light, effici, cell, film, photocatalyt, coat, photocatalyst, electron, layer, tio, . . .						
	0.009	0.624	0.004	0.001	4.427	0.000	**
53	kinet, adsorpt, activ, temperatur, studi, decomposit, surfac, experiment, adsorb, use, . . .						
	0.007	0.122	0.001	0.001	1.063	0.288	
57	materi, phase, manufactur, properti, use, composit, recycl, raw, construct, structur, . . .						
	0.007	0.199	0.001	0.000	2.684	0.007	**
61	use, acid, lignin, spectroscopi, method, result, electron, character, composit, cellulos, . . .						
	0.009	0.370	0.003	0.001	3.177	0.001	**
62	flow, numer, veloc, studi, forc, equat, experiment, number, result, channel, . . .						
	0.008	0.310	0.002	0.001	3.276	0.001	**
63	gas, natur, coal, fire, pipelin, power–ga, ptg, exist, synthet, shale, . . .						
	0.005	0.010	0.000	0.000	0.202	0.840	
70	devic, design, harvest, prototyp, thermoelectr, mechan, output, electron, effici, . . .						
	0.007	0.299	0.002	0.001	3.204	0.001	**
71	cool, air, system, condit, hot, use, perform, cold, absorpt, summer, . . .						
	0.009	0.051	0.000	0.001	0.617	0.537	
72	batteri, charg, discharg, capac, bess, lithium, flow, high, redox, use, . . .						
	0.006	0.691	0.003	0.001	5.677	0.000	**
84	water, desalin, use, fresh, seawat, produc, requir, can, consumpt, distil, . . .						
	0.006	0.003	0.000	0.000	0.028	0.977	
88	concentr, plant, csp, receiv, thermal, salt, parabol, high, field, trough, . . .						
	0.006	0.049	0.000	0.001	0.480	0.631	
90	electrod, high, electrochem, carbon, materi, densiti, perform, cycl, supercapacitor, . . .						
	0.009	1.382	0.008	0.001	7.788	0.000	**
93	activ, evolut, electrocatalyst, oxygen, reaction, high, catalyst, oer, effici, densiti, . . .						
	0.009	4.202	0.013	0.001	11.424	0.000	**
94	recoveri, product, plastic, mill, recov, industri, contamin, pulp, bio-bas, paper, . . .						
	0.005	0.098	0.000	0.000	0.935	0.350	
100	use, work, effici, energi, need, howev, high, paper, relat, base, . . .						
	0.001	0.090	0.000	0.000	1.744	0.081	

[1] Significance level: 0.1, * significance level: 0.05, ** significance level: 0.01.

Table 6. Relevant documents with weak signal topics [1].

Topics	Authors (Year)	Titles
14	Mahlia et al. (2014)	A review of available methods and development on energy storage; technology update
	Benato and Stoppato (2018)	Pumped Thermal Electricity Storage: A technology overview
	Zhou et al. (2019)	A review of thermal energy storage in compressed air energy storage system
25	Nie et al. (2017)	Risk management of energy system for identifying optimal power mix with financial-cost minimization and environmental-impact mitigation under uncertainty
	Zhen et al. (2017)	An inexact optimization model for regional electric system steady operation management considering integrated renewable resources
	Suo et al. (2017)	Identifying optimal clean-production pattern for energy systems under uncertainty through introducing carbon emission trading and green certificate schemes
31	Menor, et al. (2017)	Natural sepiolite promoted with Ni as new and efficient catalyst for the sustainable production of hydrogen by steam reforming of the biodiesel by-products glycerol
	Kathiraser et al. (2017)	Highly active and coke resistant Ni/SiO_2 catalysts for oxidative reforming of model biogas: Effect of low ceria loading
	Takano et al. (2015)	CO_2 methanation of Ni catalysts supported on tetragonal ZrO_2 doped with Ca^{2+} and Ni^{2+} ions
33	Kumar and Bhimasingu (2015)	Key Aspects of Smart Grid Design for Distribution System Automation: Architecture and Responsibilities
	Qin et al. (2019)	Optimal Network Pricing Strategy for Improving Network Operation in Local Energy Market
	Usman et al. (2018)	Losses management strategies in active distribution networks: A review
34	Wu et al. (2019)	A method to identify weak points of interconnection of renewable energy resources
	Yan et al. (2015)	The combined effects of high penetration of wind and PV on power system frequency response
	Lopez et al. (2019)	Sizing of renewable energy sources to support resilience in distribution networks
48	Gonzalez-Flores et al. (2019)	Thin film solar cells of chemically deposited SnS of cubic and orthorhombic structures
	Hao et al. (2016)	Fabrication of a TiO_2-P25/(TiO_2-P25 + TiO_2 nanotubes) junction for dye sensitized solar cells
	Lim et al. (2019)	Polyethylenimine ethoxylated interlayer-mediated ZnO interfacial engineering for high-performance and low-temperature processed flexible perovskite solar cells: A simple and viable route for one-step processed CH3NH3PbI3
57	Liu et al. (2017)	Energy absorption characteristics of sandwich structures with composite sheets and bio coconut core
	Elhamdouni et al. (2015)	Effect of Fiber Alfa on Thermophysical Characteristics of a Material based on Clay
	Boria et al. (2018)	Green sandwich structures under impact: experimental vs. numerical analysis
61	Anstey et al. (2016)	Oxidative acid treatment and characterization of new biocarbon from sustainable Miscanthus biomass
	de Vergara et al. (2014)	Polymerization and curing kinetics of furan resins under conventional and microwave heating
	Kian et ak. (2018)	Isolation and characterization of nanocrystalline cellulose from roselle-derived microcrystalline cellulose
62	Ding et al. (2016)	Numerical simulation and experimental validation for energy harvesting of single-cylinder VIVACE converter with passive turbulence control
	Sun et al. (2019)	Flow-induced vibration of tandem circular cylinders with selective roughness: Effect of spacing, damping and stiffness
	Ma et al. (2016)	Nonlinear piecewise restoring force in hydrokinetic power conversion using flow induced motions of single cylinder
70	Zhang et al. (2014)	High-performance triboelectric nanogenerator with enhanced energy density based on single-step fluorocarbon plasma treatment
	Kim et al. (2018)	Versatile nanodot-patterned Gore-Tex fabric for multiple energy harvesting in wearable and aerodynamic nanogenerators
	Ali and Yilbas (2017)	Innovative design of a thermoelectric generator of extended legs with tapering and segmented pin configuration: Thermal performance analysis

Table 6. *Cont.*

Topics	Authors (Year)	Titles
72	Dubarry and Devie (2018)	Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging
	Yahmadi et al. (2017)	Research of critical causes and improvement of energy storage system reliability in power electronic applications
	Chiang et al. (2017)	Development of a converterless energy management system for reusing automotive lithium-ion battery applied in smart-grid balancing
90	Xie et al. (2016)	Hydrothermal synthesis of layered molybdenum sulfide/N-doped graphene hybrid with enhanced supercapacitor performance
	Sun et al. (2017)	Oxygen-containing hierarchically porous carbon materials derived from wild jujube pit for high-performance supercapacitor
	Cui et al. (2017)	Dopamine adsorption precursor enables N-doped carbon sheathing of MoS2 nanoflowers for all-around enhancement of supercapacitor performance
93	Wu et al. (2016)	Cobalt diselenide nanoparticles embedded within porous carbon polyhedra as advanced electrocatalyst for oxygen reduction reaction
	Liu et al. (2018)	Confined organometallic Au1Nx single-site as an efficient bifunctional oxygen electrocatalyst
	Hu et al. (2019)	Facile synthesis of mesoporous WS2 for water oxidation

[1] Only relevant documents for topics with a *p*-value of 0.05 or less are presented.

As shown in Table 6, Topic 14 is a discussion of energy storage devices, especially compressed air energy storage (CAES), to manage renewable energy with intermittent output. Topic 25 is about optimally integrating renewable energy into an energy or power supply system. Topic 31 discusses the role of various catalysts used in bioenergy. Topic 33 discusses the strategy of building a distribution network that efficiently manages distributed power sources such as renewable energy. Topic 34 deals with challenges such as frequency response, network interconnection, and network resilience that occur in the transmission and distribution network sector when the share of renewable energy increases in the future. Topic 48 deals with the discussion of advances in photocatalyst technology to increase the efficiency of solar cells. Topic 57 is about pursuing sustainable development using materials based on renewable sources, and Topic 61 includes studies on measuring the energy level of biomaterials. Topic 62 mainly focuses on studies examining flow-induced turbulence, vibration, and motions. Topic 70 has discussions about energy harvesting technologies such as nanogenerators. Topic 72 is a study to search for alternatives to increase the durability and reliability of batteries. Topic 90 is a discussion on material improvement to enhance the performance of a supercapacitor, one of the energy storage devices. Topic 93 discusses advanced electrocatalysts for water oxidation.

4.3. NSWK Signals

As shown in Table 7, of the 100 topics, a total of 20 were included in the NSWK signal. Additionally, in the second half of the 2010s, there were 14 topics with *p*-values lower than the significance level of 0.05. Among the topics selected for NSWK signals, the topics with a *p*-value lower than the significance level of 0.05 are as follows.

Table 7. Topics selected as not-strong-but-well-known (NSWK) signals.

Topics	Keywords						
	Mean	**Inc.**	**Estimate**	**Std.Error**	**t-Value**	**Pr(>|t|)** [1]	
4	develop, industri, china, promot, rapid, structur, renew, paper, new, taiwan, ...						
	0.010	−0.276	−0.003	0.000	−9.858	0.000	**
6	energi, renew, sourc, effici, util, primari, consumpt, base, usag, convers, ...						
	0.027	−0.124	−0.004	0.000	−8.750	0.000	**
9	will, new, need, world, mani, one, problem, way, becom, import, ...						
	0.019	−0.340	−0.008	0.001	−11.423	0.000	**
15	sustain, environment, econom, environ, pollut, social, improv, benefit, qualiti, ...						
	0.010	−0.118	−0.001	0.000	−3.457	0.001	**
17	hydrogen, cell, fuel, product, electrolysi, produc, electrolyz, effici, electrolys, hydrid, ...						
	0.011	−0.048	−0.001	0.001	−0.635	0.525	
22	polici, govern, state, renew, support, implement, promot, regulatori, regul, maker, ...						
	0.014	−0.311	−0.005	0.001	−7.588	0.000	**
29	product, input, indic, emergi, effici, ratio, indirect, consumpt, farm, non-renew ...						
	0.012	−0.182	−0.002	0.001	−2.951	0.003	**
40	research, review, discuss, applic, recent, paper, present, futur, challeng, issu ...						
	0.027	−0.020	−0.001	0.001	−0.681	0.496	
41	wind, farm, speed, turbin, offshor, instal, capac, power, locat, densiti, ...						
	0.011	−0.234	−0.003	0.001	−4.517	0.000	**
46	scenario, capac, nuclear, futur, share, high, demand, mix, renew, option, ...						
	0.015	−0.001	0.000	0.001	−0.038	0.970	
47	target, european, res, achiev, goal, sector, nation, europ, direct, union, ...						
	0.014	−0.297	−0.005	0.001	−7.838	0.000	**
54	emiss, reduct, greenhous, reduc, ghg, sector, mitig, gase, consumpt, compar, ...						
	0.012	−0.139	−0.002	0.001	−2.850	0.004	**
65	resourc, demand, current, energi, sector, futur, status, growth, potenti, crisi, ...						
	0.015	−0.361	−0.007	0.001	−7.933	0.000	**
68	econom, year, per, net, annual, estim, total, valu, million, period, ...						
	0.012	−0.146	−0.002	0.001	−2.793	0.005	**
69	photovolta, instal, panel, modul, year, averag, month, perform, array, irradi, ...						
	0.011	−0.066	−0.001	0.001	−1.109	0.268	
78	public, household, accept, survey, factor, adopt, prefer, influenc, educ, level, ...						
	0.017	−0.131	−0.002	0.001	−2.116	0.034	*
81	incent, scheme, tariff, subsidi, mechan, renew, support, tax, feed-, fit, ...						
	0.012	−0.313	−0.004	0.001	−5.636	0.000	**
85	impact, environment, assess, life, cycl, compar, lca, categori, potenti, global, ...						
	0.014	−0.047	−0.001	0.001	−0.786	0.432	
89	power, plant, oper, unit, output, combin, fluctuat, thermal, coal-fir, capac, ...						
	0.013	−0.010	0.000	0.000	−0.309	0.757	
95	project, local, communiti, rural, implement, access, initi, program, support, develop, ...						
	0.011	−0.285	−0.004	0.001	−5.941	0.000	**

[1] Significance level: 0.1, * significance level: 0.05, ** significance level: 0.01.

As shown in Table 8, Topic 4 discusses the status, strategy, policies, and prospects of renewable energy in China and Taiwan. Topic 6 covers the entire renewable energy resources, for example, the current status, prospects, and policies. Topic 9 discusses sustainable energy and future planning. Topic 15 has a number of discussions on sustainable development of energy and economic growth. Topic 22 deals with the impact of countries' renewable energy policies and regulations. Topic 29 discusses the ratio of renewable and

non-renewable energy used to produce grain in farms, energy efficiency, and economic comparison between renewable and non-renewable energy. Topic 41 mainly discusses the potential evaluation of wind energy. Topic 47 has a number of studies on renewable energy goals in the European Union and means of implementation to achieve them. Topic 54 consists of studies that evaluate CO_2 reduction goals and policies. Topic 65 deals with national policies, such as the potential for renewable energy. Topic 68 is mainly about economic evaluation and economic analysis of renewable energy. Topic 78 deals with public acceptance, such as intention to pay for renewable energy and willingness to use it. Topic 81 discusses renewable energy support systems and incentives such as FiT and RPS. Finally, Topic 95 addresses the benefits of community renewable energy (CRE) projects.

Table 8. Relevant documents with NSWK signal topics [1].

Topics	Authors (Year)	Titles
4	Liou (2010)	Overview of the photovoltaic technology status and perspective in Taiwan
	Chang and Lee (2016)	Taiwan's renewable energy strategy and energy-intensive industrial policy
	Liu et al. (2011)	A survey of China's low-carbon application practice—Opportunity goes with challenge
6	Siraj (2012)	Energy resources—The ultimate solution
	Augutis et al. (2014)	Impact of the Renewable Energy Sources on the Energy Security
	Amigues et al. (2015)	Equilibrium transitions from non-renewable energy to renewable energy under capacity constraints
9	Kakegawa (2017)	Smart & Safe Energy Society
	Cash (2018)	Choices on the road to the clean energy future
	Abbasi et al. (2011)	The return to renewables: Will it help in global warming control?
15	Bilgen and Sarıkaya (2015)	Exergy for environment, ecology and sustainable development
	Zuo and Ai (2011)	Environment, energy and sustainable economic growth
	Duić et al. (2013)	Sustainable development of energy, water and environment systems
22	Berg (2013)	Regulatory Functions Affecting Renewable Energy in Developing Countries
	Baldwin (2019)	Why do countries emulate each others' policies? A global study of renewable energy policy diffusion
	McKane et al. (2017)	Improving the relevance and impact of international standards for global climate change mitigation and increased energy access
29	Unakıtan and Aydın (2018)	A comparison of energy use efficiency and economic analysis of wheat and sunflower production in Turkey: A case study in Thrace Region
	Kazemi et al. (2015)	Energy analysis for faba bean production: A case study in Golestan province, Iran
	Sahabi et al. (2016)	Is saffron more energy and economic efficient than wheat in crop rotation systems in northeast Iran?
41	Shu et al. (2015)	Statistical analysis of wind characteristics and wind energy potential in Hong Kong
	Dabbaghiyan et al. (2016)	Evaluation of wind energy potential in province of Bushehr, Iran
	Ritter et al. (2015)	Designing an index for assessing wind energy potential
47	Veum and Bauknecht (2019)	How to reach the EU renewables target by 2030? An analysis of the governance framework
	Liobikienė and Butkus (2017)	The European Union possibilities to achieve targets of Europe 2020 and Paris agreement climate policy
	Aune et al. (2012)	Implementing the EU renewable target through green certificate markets
54	Kusumadewi et al. (2017)	GHG Mitigation in Power Sector: Analyzes of Renewable Energy Potential for Thailand's NDC Roadmap in 2030
	Sano et al. (2015)	Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro- and sectoral decomposition analyses
	Mittal et al. (2016)	Bridging greenhouse gas emissions and renewable energy deployment target: Comparative assessment of China and India
65	Poudyal et al. (2019)	Mitigating the current energy crisis in Nepal with renewable energy sources
	Halder et al. (2015)	Energy scarcity and potential of renewable energy in Bangladesh
	Kousksou et al. (2015)	Renewable energy potential and national policy directions for sustainable development in Morocco

Table 8. *Cont.*

Topics	Authors (Year)	Titles
68	Park et al. (2016)	Can Renewable Energy Replace Nuclear Power in Korea? An Economic Valuation Analysis
	Shih and Tseng (2014)	Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach
	Gürtürk (2019)	Economic feasibility of solar power plants based on PV module with levelized cost analysis
78	Kostakis and Sardianou (2012)	Which factors affect the willingness of tourists to pay for renewable energy?
	Halder et al. (2016)	The Theory of Planned Behavior model and students' intentions to use bioenergy: A cross-cultural perspective
	Cacciatore et al. (2012)	Labeling renewable energies: How the language surrounding biofuels can influence its public acceptance
81	Meus et al. (2019)	On international renewable cooperation mechanisms: The impact of national RES-E support schemes
	Oak et al. (2014)	Performance comparison of renewable incentive schemes using optimal control
	Zhang et al. (2018)	Substitution effect of renewable portfolio standards and renewable energy certificate trading for feed-in tariff
95	Walker et al. (2014)	Community benefits, framing and the social acceptance of offshore wind farms: an experimental study in England
	Chaichana et al. (2017)	Promoting Community Renewable Energy as a tool for Sustainable Development in Rural Areas of Thailand
	Walker et al. (2010)	Trust and community: Exploring the meanings, contexts and dynamics of community renewable energy

[1] Only relevant documents for topics with a *p*-value of 0.05 or less are presented.

5. Discussion

5.1. Strong Signals

As shown in Figure 4 and Table 3, it is confirmed that Topic 92 is one of the prominent topics in strong signals. Topic 92 concerns an algorithm for solving the problem of optimal power flow incorporating renewable energy sources. In the process of deriving the optimal integration plan for renewable energy, different regions [53], different renewable energies [54], and several objectives such as emission minimization, fuel cost minimization, voltage profile improvement, and transmission power loss minimization [55] are considered together. As the proportion of intermittent power sources such as solar and wind power increases, it becomes more important to build an optimization model that comprehensively considers the economy, environment, and technical efficiency of the power system.

Next, it is necessary to look at Topic 73 among the topics that have a relatively high topic proportion and a statistically significant increase rate. Topic 73 focuses on the social implications of energy transitions towards renewable energy. In order for energy transitions to succeed, technological innovation and policy and institutional improvement are important, but social interest and participation in energy transitions is also a significant task. Accordingly, research is being actively conducted to review social discourses related to energy transitions, and efforts to increase the acceptance of energy transitions, which focus on expanding the supply of eco-friendly renewable energy, have recently become more emphasized.

In addition, in Topic 66, it is confirmed that the link between microgrids and demand response is receiving strong interest. As an effective form of distributed power integration, microgrids have developed rapidly and played an important role in the consumption of renewable energy [56]. The demand-side response has a positive impact on the operation of microgrids by reducing load fluctuations from renewable energy. However, the demand response also contains uncertainties. How to deal with the uncertainty of renewable energy and demand response when using microgrids has emerged as an important issue [57].

Topic 76 has a similar theme to Topic 66. However, rather than focusing on microgrids and demand response, discussions on smart grids that can flexibly connect renewable energy to the system are the main focus. In addition, issues such as "frequency control strategy in microgrids" in Topic 77 and "renewable energy generation prediction" in Topic 49 stand out relatively compared to other strong signals.

In short, research on modeling a method for optimally integrating renewable energy into the power grid is receiving great attention. In addition, interest in topics such as microgrids, demand response, and smart grids that can flexibly handle the intermittent output of renewable energy is increasing. In the same context, studies on predicting the irregular output of renewable energy are being actively conducted. Furthermore, it was confirmed that not only technical issues but also social discourse studies occupied a considerable proportion.

5.2. Weak Signals

As shown in Figure 4 and Table 5, the topic with the highest growth rate among weak signals is Topic 93. The topic focuses on efficient electrocatalysts for oxygen reduction reaction (ORR) or oxygen evolution reaction (OER). This issue is growing rapidly as the use of hydrogen-based fuel cells increases in the power generation and transportation sectors. The increase in the proportion of renewable energy with intermittent output is also increasing the utilization of hydrogen. When renewable energy sources, such as wind power and solar energy, which are highly affected by the weather, are over-produced, the method of converting them to hydrogen and utilizing them is attracting attention [58].

Topic 90 about supercapacitors also shows a higher rate of growth compared to other topics. Supercapacitors can ramp up or down quickly by discharging or charging within a few seconds [59]. In contrast, it takes 10–60 min for a battery to fully discharge, while a gas turbine can take nearly 30 min to reach full speed [60]. So far, this makes supercapacitors technically one of the best candidates to provide high ramping, which is required due to the high solar penetration rate on peak load days [61].

Topics 72 and 48 also show relatively high growth rates. Topic 72 focuses on battery durability and reliability. As the number of battery energy storage systems and their grid applications increase, it is necessary to better understand and predict battery cell degradation. When determining the operational and commercial risks associated with the deployment of battery energy storage systems (BESS), it is imperative to accurately predict their durability under different usage modes [62]. Topic 48 is a topic on the performance of photocatalytics used in photovoltaic power generation. The simple synthesis and environmental application of photocatalysts with excellent photocatalytic capabilities remains a huge challenge, and new trials such as silver-based semiconductor modified TiO_2 nanotube arrays are receiving a lot of attention [63]. In addition, Topic 14 of CAES, Topic 31 of catalysts for bio-energy, Topic 61 of energy level of bio-materials, and Topic 33 of advanced distribution networks showed high growth rates.

In weak signals, discussions related to energy storage devices showed a relatively high rate of increase, and interest in large-capacity energy storage systems such as hydrogen, supercapacitors, and CAES also showed a high rate of increase. In addition, the problem of improving the durability and reliability of batteries was also highlighted. Furthermore, the discussion of new catalysts for improving bioenergy efficiency was selected as one of main weak signals.

5.3. NSWK Signals

As shown in Figure 4 and Table 7, among NSWK signals, Topic 6 is the topic with the highest topic proportion. Topic 6 mainly deals with the current status, prospects, and policies of renewable energy sources. These topics now account for a large portion of renewable energy research. However, the increasing rate was negative because there was a lot of research on topics related to the overall renewable energy, for example, renewable energy development situations, reserves, potentials, obstacles, and efficiency. In the case of

Topic 6, there are many studies on the status of renewable energy by country or city, for example, the status and overview of renewable energy potential in Cote d'Ivoire [64], the development situation and obstacles of Beijing's renewable energy industry [65], status, barriers, and efforts to utilize wind energy in Pakistan [66], the evaluation of renewable energy reserves in Taiwan [67], and an overview of marine renewable energy resources in South Korea [68].

Topic 9 has the second-highest topic proportion among the NSWK signals which is statistically significant, with a relatively low increase rate. Topic 9 mainly deals with sustainable energy and future planning. In particular, there are many studies on sustainable development and energy. The paradigm of sustainable development was proposed at the UN conference, which was held under the title "Earth Summit" in 1992 [69].

There are studies which have raised the issue of sustainable energy. Breyer et al. [70] indicated that mankind has reached its present crisis level because of unsustainable energy systems. Hughes and Rudolph [71] pointed out that most of the oil products consumed by humans come from non-renewable sources, and that society should prepare for a world with less oil.

Topic 78 had the third highest topic proportion. Topic 78 consists of studies on public acceptance, such as intention to pay for renewable energy and willingness to use it. Acceptance, considered one of the obstacles to the supply and expansion of renewable energy, is a problem related to people's universal perception and is being researched a lot. Zyadin et al. [72] stated that increasing public knowledge and awareness has a positive correlation with public support for renewable energy development.

There are also many studies on renewable energy education to increase acceptance. Guven and Sulun [73] indicated that more compulsory subjects should be provided on renewable energy issues and more comprehensive information on renewable energy issues should be included in teacher education. Zyadin et al. [74] argued that it is important to provide renewable energy education as early as possible to encourage renewable energy development.

In addition to its acceptance, research on the intention of paying for renewable energy also had a high topic proportion. Oliver et al. [75] stated that the view that green electricity is reliable, that it is involved in recycling waste, and the belief that everyone should contribute to the generation of green electricity leads the willingness to pay (WTP). Kostakis and Sardianou [76] found that family status (married and having children) and level of education are not statistically significant to the willingness to pay a premium for accommodation in hotels with renewable energy sources. Xie and Zhao [77] indicated that the main drivers of positive WTP for green electricity are renewable energy knowledge, belief in the government, behavior, education, and history of respiratory diseases.

Topic 65 had the lowest increasing rate among NSWK signals. Topic 65 has a large number of studies on national policies such as renewable energy potential by country. For example, studies covering Bangladesh include energy security and renewable energy activation [78], and the status and prospects of renewable energy [79,80]. Research covering Pakistan includes renewable energy sources in power generation [81], the development of solar power railway transportation systems, and the evaluation of solar energy potential [82]. Research covering Nigeria includes the state of renewable energy and future prospects [83], the status of solar integration and policies of solar energy [84], renewable energy technology for power generation [85], and the potential of renewable energy [86]. In addition, Topic 65 has studies on the status and policies of renewable energy in countries such as Malaysia, Uganda, Nepal, Iraq, and Morocco.

Additionally, NSWK signals include Topic 47 on EU renewable energy targets and means of implementation to achieve them, Topic 22 on the impact of national renewable energy policies and regulations, and Topic 68 on the economic assessment and analysis of renewable energy. NSWK signals include many studies about the basic content of renewable energy such as status, prospects, and policies, as well as general and comprehensive content such as reserves, potentials, obstacles, and efficiency. It also includes research

on public acceptance such as the intention and willingness to pay for sustainable and renewable energy for the future.

6. Conclusions

In this study, 100 topics from the 2010s (2010–2019) were extracted from academic abstracts on renewable energy, and then various signals were searched by applying the concept of weak signals. While the existing research on renewable energy topic analysis centered on LDA, a popular probabilistic topic modeling method, this study utilized STM, which has strengths in testing statistical hypotheses. Furthermore, based on the topic proportion, future signs such as strong signals, weak signals, and NSWK signals were comprehensively examined.

The contributions of this study compared to previous studies are as follows. First, this study presented renewable energy topics with statistically significant increases in topic proportion within the years 2010–2019. Based on the results, it reviewed which topics correspond to strong signals with high interest and a high increase rate of interest, weak signals with low interest but high increase rate of interest, and NSWK signals with high topic proportion but low increase in interest. Second, in order to facilitate the interpretation of the topics, related documents as well as the keywords of topics were presented. In other words, it helped readers interpret the topics by showing documents representing the topics.

The approach of this study can be used to look at trends in all fields, not just renewable energy. If the text data of a field to be studied can be obtained, this approach can provide the basis for intuitive understanding of changes in topics in the field. In particular, by combining STM with weak signal-based future sign detection techniques, limitations of existing techniques such as the problem of some signals disappearing and difficulty in interpretation could be overcome.

Through the results of this study, the implications related to renewable energy research are examined. Research on topics in strong signals and NSWK signals is generally actively underway. The topics included in the weak signals are not yet high in weight but belong to the category with a high growth rate. Accordingly, there is a need to increase interest in topics included in weak signals in the direction of renewable energy research. In weak signals, research on large-capacity storage systems has been included. As renewable energy expands and the role of storage devices becomes more important, demand for large-capacity storage systems is also rapidly increasing. Research on additional alternatives such as hydrogen and CAES is important as well as pumped hydro energy storage that has already been widely commercialized. In addition to expanding the capacity of the storage systems, studies on improving the durability and reliability of batteries need to be strengthened. Additionally, it is necessary to construct a diverse renewable energy portfolio in the energy system by improving the efficiency of bioenergy as well as solar and wind power.

However, there are still challenges to be addressed. People pay attention to weak signals in particular as future signs because there is an expectation that weak signals may become strong signals in the future. However, not all weak signals are converted to strong signals. Therefore, future studies need to look at which weak signals are likely to convert to strong signals. Since this task has been steadily emphasized in previous studies, it is necessary to be actively carried out in further studies. Additionally, while classifying several signals, the mean of the average topic proportions was used as a dividing line on the x-axis, and the mean value varies depending on the number of samples. In this study, the average value of 100 topics was used, and as the number of topics changes, the division line moves with it. Therefore, this division line cannot be an absolute criterion. Further research needs to discuss how to establish more convincing criteria for classification. In addition, this study used only ScienceDirect data, but it is necessary to increase the validity of the study results by securing more abundant data in future studies.

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