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ScienceDirect
Technological Forecasting & Social Change 75 (2008) 771–782
Technological Forecasting and Social Change

Tracking emerging technologies in energy research: Toward a roadmap for sustainable energy

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Received 25 April 2007; received in revised form 29 May 2007; accepted 31 May 2007

Abstract

Science and technology for renewable and sustainable energy are indispensable for our future society and economics. To meet the goal of sustainable energy development, there is a growing body of research efforts world wide. The planner of energy research has to grasp the broader coverage of scientific and technological research, and make decisions on effective investment in promising and emerging technologies especially under circumstances of limited resources. In this paper, we track emerging research domains in energy research by using citation network analysis. Our analysis confirms that the fuel cell and solar cell are rapidly growing domains in energy research. We further investigate the detailed structure of these two domains by clustering publications in these domains. Each citation cluster has characteristic research topics, and there is a variety of growth trends among the clusters. By using citation network analysis, we can track emerging research domains among a pile of publications efficiently and effectively.

Keywords: Emerging technologies; Forecasting; Citation network; Bibliometrics; Sustainable energy; Renewable energy

1. Introduction

Energy is a key element for our society and also a key input for economic development. Sustainable energy and renewable energy have been widely accepted as a key concept for our common future [1–3]. Nowadays, it is often warned that our current energy system is not sustainable. In 2001, 80% of world

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0040-1625/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2007.05.005

primary energy use is from fossil fuels, and they play an important role in the transport and stationary energy sectors, including electric power generation [4]. But the production of fossil fuel is predicted to decline as early as the middle of this century [1]. Additionally, the combustion of fossil fuels has played a dominant role in the emission of greenhouse gases (GHG) into the atmosphere [2]. There is an urgent need to develop highly efficient energy utilization processes and substitute energy sources as a countermeasure against the CO_2 problem, in addition to current renewable energy power plants, i.e., hydraulic power plants.

The saving of primary energy from fossil fuels and the promotion of exploitation of renewable sources are two of the most relevant goals to be achieved in order to match the climate protection target fixed by the Kyoto Protocol in 1997. Even though conventional sources, such as oil, natural gas, and coal meet most of the energy demand at the moment, the role of renewable energy sources and their current advances have to take more relevance in order to contribute to future energy supply and support the energy conservation strategy. In industrialized countries, there is a tendency to change strategies. The Kyoto Protocol impacts on policy development at various levels from regional, national, and world wide [5–12].

To meet the goal of sustainable energy development, there is a growing body of research efforts and publications world wide, while there are a variety of research priorities among countries [13,14]. Investment for technological innovation is an inevitable first step for future sustainable energy systems. The planner of energy research has to grasp the broader coverage of scientific and technological research, and make decisions on effective investment in promising and emerging technologies especially under circumstances where total budget is constrained or has declined [15]. Technological forecasting [16–18] and technology roadmapping [19–21] are expected to meet this challenge. Fig. 1 is a schematic illustration to compare these two approaches.

Forecasting is descriptive approach based on retrospective data from past to present [22]. By extrapolating current trends to the future, we can predict future trends and obtain a prospective perspective. Qualitative methods of forecasting include Delphi and scenarios, and quantitative methods are extrapolations of a time series of growth curves using logistic or Gompertz functions [16]. Roadmapping is normative approach and includes backcasting from vision to present status along the pathways to realize the vision [22]. These two approaches are not contradictory but compatible. Vision is usually given by a top–down approach based on the expert's experience and intuition, but the feasibility should be tested against existing data and trends. Kostoff and Schaller pointed out that one of the critical factors in high-quality roadmaps is global data awareness [19]. In this sense, policy makers and R&D

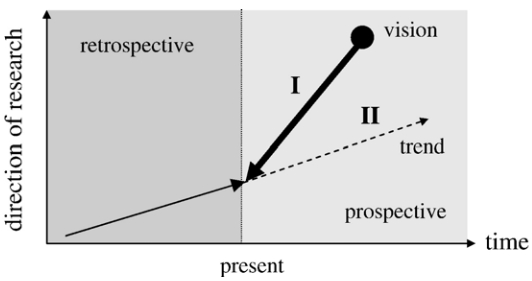


Fig. 1. Schematic illustration of technological forecasting and roadmapping. The arrow (I) is backcasting from vision to present. The dashed arrow is forecasting by extrapolation of the current trend.

managers have to notice global trends in research and emerging technologies among a pile of literature, which enables precise forecasting and effective roadmapping.

In today's increasingly knowledge-based economy, growth more reliably depends on the application of new science and technology. Therefore, for R&D managers and policy makers, noticing emerging research domains among numerous academic papers has become a significant task. Generally, there are two approaches to obtain global data awareness [19]. One straightforward manner is the expert-based approach, which utilizes the implicit knowledge of domain experts. The other is the computer-based approach, which analyzes explicit knowledge such as newspapers, magazines, and academic papers. However, the former approach is becoming a highly difficult task because of a flood of information. In addition to the increasing amount of information, the fact that the individual scientist has to focus on or specialize in only a few scientific sub-domains to keep up with the growth of the domains makes the former approach highly laborious, time consuming, and subjective.

A major advance of the past few years in roadmapping has been using a computer to support the expert-based approach. Data mining (DM) and database tomography (DT) have become practical techniques for assisting the forecaster to identify the taxonomic structure of a research domain [23–26], as well as early signs of technological change [27]. A computer-based approach can complement the expert-based approach because it is compatible with the scale of information. There are two types of methodology for the computer-based approach: text mining and link mining. An example of the former is performed by Kostoff et al. [23–26]. They analyzed multi-word phrase frequencies and phrase proximities, and extracted the taxonomic structure of energy research. A citation-based approach is the latter type of methodology. In previous works, citation-based approaches were used to describe the network of energy-related journals using journal citation data [13] or journal classification data [28]. Recently, Small explored the possibility of using co-citation clusters over three time periods to track the emergence and growth of research areas, and predict their near-term changes [27]. In the citation-based approach, it is assumed that citing and cited papers have similar research topics. By clustering the citation network, we can detect a research front consisting of a group of papers. The aim of this paper is to offer a global structure of energy research and to detect emerging technologies there by using citation network analysis. Our results can offer an intellectual basis for constructing an energy roadmap.

2. Data and methods

We collected citation data of energy-related publications from the Science Citation Index (SCI) compiled by the Institute for Scientific Information (ISI). We used the Web of Science, which is a Web-based user interface of ISI's citation databases. It is not a rudimentary task to define a research domain. At first, we tried to collect energy-related papers by the simple query, *energy*. But the collected papers

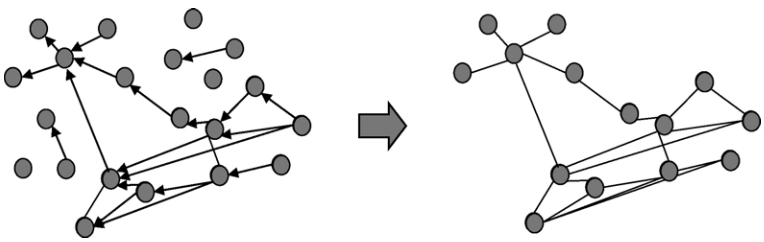


Fig. 2. Schematics of the process to convert the retrieved data into the maximum connected component.

included a variety of not energy-related topics and were noisy. Therefore, we searched papers based of the category of the journal where they were published. Bibliographic records of 152,514 papers published in the 68 journals classified by the SCI under the category of Energy and Fuels were collected. Some of these papers may be not relevant to energy research even though they are published as energy-related research, because we collected data simply by journal titles as a clue. Therefore, we focused on the maximum connected component, which currently has 53,033 papers (34.8%). In other words, we regarded papers not citing other papers in the component as digressional. When papers cite no other papers in the component and are not cited by the other papers in the component, they are not included in the component. We consider that it is hard for such papers to be influential to determine the future trend of energy research. Then, the network is converted into a non-weighted, non-directed network as seen in Fig. 2. Finally, the network is divided into clusters using the topological clustering method [29,30]. The clustering is not fuzzy.

After clustering the network, we analyzed the characteristics of each cluster by the titles and abstracts of papers that are frequently cited by the other papers in the cluster, as well as the journals in which the papers in the cluster were published. We named each cluster and also listed the keywords for each cluster from the titles and abstracts of the top twenty most cited papers in the cluster. The average publication year of papers in each cluster was calculated to know the emerging research field. We used the average publication year as a clue to tracking emerging technologies in energy research.

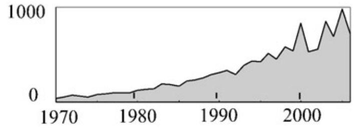
3. Results and discussion

Table 1 shows the characteristics of the top ten clusters in energy research. *Combustion* (Cluster E_1) is the largest cluster among them. The reaction mechanism of a flame in turbulent flow is the main topic discussed in Cluster E_1. The number of publications monotonically increases after the 1970s, while some dips are observed after 2000. *Coal* (Cluster E_2) is the second largest, and the liquefaction and gasification of coal and char are principally studies, but have a low growth rate in publication. The oldest average year of publication of this cluster (1994.1) reflects this fact. Cluster E_3 (*Battery*) is relatively new and emerging among the top ten clusters, and its average publication year is 1997.9. Cluster$_4$ (*Petroleum*) is as old as Cluster E_2 (*Coal*).

Cluster E_5 (*Fuel cell*) shows remarkably different growth curves. In sharp contrast to the above clusters, publications drastically increase after around 2000. Cluster E_6 (*Wastewater*) also shows discontinuous increases after 1991. But this cluster seems to be noisy from the perspective of sustainable energy. In E_6, treatment of wastewater such as textile dye is mainly discussed, while only a small fraction of papers study sustainable energy, e.g., biomass. This inclusion of a noisy cluster is attributed to our selection of corpus, i.e., we simply collected papers from journal categories of ISI to know the global trend of energy research but not form queries. Among the rest of the clusters, Cluster E_9 (*Solar cell*) is the youngest and has the largest number of publications after 1990. In Table 1, we showed only the top ten clusters. Other clusters are the geology of petroleum and oil-recovery process, but occupy a small fraction of the network.

From the growth curve in Table 1, Cluster E_2 (Fuel cell) and E_6 (Solar cell) seem to be emerging research domains. In particular, the Fuel cell cluster is the youngest among the top ten clusters. Therefore, we further investigated these two research domains in detail. We recollected the bibliographic records by using fuel cell* and solar cell* as a query for each domain. Although a certain set of queries is desirable to precisely define each domain, we used such simple queries for convenience. The data include 15,600 records for the fuel cell and 16,199 records for the solar cell. The maximum connected components are 12,388 papers (79.4%) for the fuel cell and 13,682 papers (84.5%) for the solar cell. After clustering the components, young clusters are further divided into sub-clusters to track the emerging research domains there.

Table 1
Characteristics of the top ten clusters in energy research

Cluster no.	Cluster name	Keywords	Number of papers	Average year	Growth curve (1970–2005)
E_1	Combustion	Flame, turbulent, reaction mechanism, soot, kinetics	12,128	1995.7	
E_2	Coal	Liquefaction, gasification, coal char, combustion	11,904	1994.1	
E_3	Battery	Electrochemistry, lithium-ion batteries. electrode, capacitor	8123	1997.9	
E_4	Petroleum	Asphaltene, resin, combustion, pylolysis, tar sand	5017	1994.5	
E_5	Fuel cell	Proton exchange, membrane, methanol, crossover	1704	2002.1	
E_6	Wastewater	Pollution, waste disposal, biomass, textile dye	1619	1999.3	
E_7	Heat pump	Heat pumping, heat transfer, absorption, hysteresis	1413	1997.3	
E_8	Engine	Carnot engine, heat engine, thermoeconomics	1204	1999.0	
E_9	Solar cell	Photovoltaic, silicon, organic, thin film, solar energy	1131	2000.6	
E_{10}	Power system	Synchronous machine, circuit, motor, lord	813	1996.7	

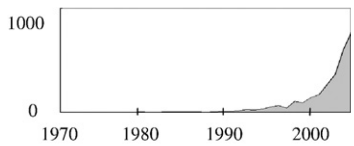
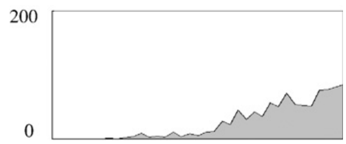
In the growth curve graph, the horizontal axis is the publication year from 1970 to 2005. The vertical axis is the number of papers in each cluster in each year. The maximum of the vertical axis is 1000 (E_1–E_3), 500 (E_4 and E_5), and 300 (E_6–E_{10}).

For the fuel cell, the citation network can mainly be divided into four clusters (Table 2), i.e., PEFC (polymer electrolyte fuel cell), SOFC (solid oxide fuel cell), DMFC (direct methanol fuel cell), and MCFC (molten carbonate fuel cell). The classification schema mainly according to the type of electrolyte material is often used in fuel cell research. Our results also accords with this classification schema. Except for Cluster F_4 (MCFC), the clusters show similar growth curves and can be regarded as young, emerging domains. Therefore, we regarded Clusters F_1, F_2, F_3 as emerging domains and performed further clustering of these clusters.

The results are shown in Table 3. F_1 (PEFC) can be mainly divided into three clusters, i.e., *Crossover*, *Modeling*, and *Proton conductivity*. Each cluster can be further divided into sub-clusters. For example, the cluster Crossover can be divided into DMFC and Crossover, Membrane and methanol permeation, Microbial fuel cell, and Micro devices. Similarly, we divided F_1, F_2, and F_3 into sub-clusters as shown in Table 3. When we analyze at the third level, we can find strong link between PEFC and DMFC. In the PEFC cluster, topics related to DMFC such as methanol permeation are found. This is a reasonable result because DMFC uses polymer electrolytes and can therefore be regarded as one type of PEFC. The result that DMFC-related topics appear at the Crossover cluster of PEFC suggests that crossover of substances such as methanol and water is a common problem with PEFC and DMFC, and the development of electrolyte membranes with high permeation resistance is the key to commercializing these devices for the use of hand phones and computer batteries.

Table 4 is a result of first-level clustering in the solar cell. The citation network of solar cell research can be divided according to the material used in the cell. The growth curve seems to be classified into

Table 2
Top four clusters in fuel cell research

Cluster no.	Cluster name	Keywords	Number of papers	Average year	Growth curve (1970–2005)
F_1	PEFC	Polymer electrolyte, proton-exchange membrane,	3834	2003.0	
F_2	SOFC	Ceramic, perovskite-type oxides, ceria-based oxides	3598	2001.5	
F_3	DMFC	Methanol-electro-oxidation, electro-catalyst	3213	2002.4	
F_4	MCFC	Molten carbonate, solubility, polarization	1046	1998.6	

The maximum of the vertical axis is 1000 (F_1–F_3) and 200 (F_4).

three types. One is the smooth increase as shown in S_1 and S_2. The second is the rapid increase after the late 90s as seen in S_3 and S_4. The third is a constant rate of publication (S_5). It is worth noting that there is small variance, for example, the number of publications in S_1 drops from the late 1980s and increases

Table 3
Hierarchical structure of fuel cell research

Level 0	Level 1	Level 2	Level 3
Fuel cell 12,388; 2001.7	PEFC 3834; 2003.0	Crossover 1,303; 2003.0	DMFC and crossover 514; 2003.0
			Membrane and methanol permeation 350; 2003.8
			Microbial fuel cells 251; 2000.9
			Micro devices 164; 2004.4
		Modeling 1,275; 2002.7	Catalyst layer of polymer electrolyte 501; 2001.4
			Mathematical model 486; 2003.6
			Measurement of current distribution and water transport 244; 2003.6
		Proton conductivity 1,204; 2003.3	Proton conductivity and water uptake 429; 2002.5
			High-temperature operation 361; 2003.3
			New polymer membrane 356; 2004.2
	SOFC 3598; 2001.5	Electrolytes 1077; 2001.7	Doped lanthanum gallate electrolyte 300; 2001.7
			Ceria based electrolytes 267; 2001.5
			Thin electrolytes 250; 2002.1
			YSZ and Al_2O_3 composites 116; 2001.8
			Hydrogen sulfide fuel cell 95; 2001.2
		Anode and modeling SOFC 1,046; 2002.2	Ni-YSZ cermet 301; 2001.4
			Modeling 299; 2002.5
			Direct oxidation 297; 2003.1
		Cathode, electrodes, Interconnects 85; 2001.0	Processing and sintering 424; 1999.4
			(La, Sr)MnO_3 and 265; 2001.5
			Interconnects 181; 2003.2
			Vapor deposition 85; 2003.0
		Modeling 234; 1998.1	
	DMFC 3,213; 2002.4	Hydrogen generation and CO oxidation 1123; 2003.2	Hydrogen generation 289; 2003.4
			CO oxidation 265; 2003.4
			Ethanol reforming (Cu–Zn–Al catalysts) 233; 2003.3
			Ethanol reforming (other metal catalysts) 183; 2003.3
		Anode and electrochemical reactions 1081; 2002.4	methanol oxidation 423; 2002.9
			O_2 reduction 386; 2002.1
			Oxidation of H_2 and CO 242; 2002.3
		Catalysts and nano-carbon 683; 2001.5	Catalysts supported by carbon nanotube 206; 2003.0
			Catalysts (Pt) 191; 1998.5
			Catalysts supported by porous carbon 121; 2003.0
			Direct ethanol fuel cell 88; 2003.6
		Borohydride 213; 2001.1	

In each column, the name of the cluster, number of papers in the cluster, and average year of publication are shown.

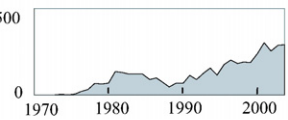
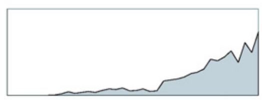
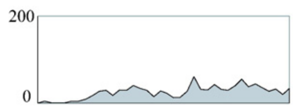
again after the 1990s. Clusters S_3 and S_4 are definitely young and rapidly developing among these clusters Therefore, we regard Clusters S_3 and S_4 as emerging domains and performed further clustering of these clusters. Cluster S_5 is the oldest and has not expanded recently. Therefore, we did not perform further clustering. Clusters S_1 and S_2 are old compared to Clusters S_3 and S_4, but might include rapidly growing areas within it. Therefore, a part of S_1 and S_2 were also clustered.

The results are shown in Table 5. The third-level sub-clusters of S_1 and S_2 were tracked only when the second-level cluster was the youngest in S_1 and S_2. For example, the cluster Limitation and modification of efficiency is the youngest second-level cluster in S_1, which includes the third-level clusters Theoretical modeling, Effect of impurities and defects, and Quantum well solar cells within it. As shown in Table 4, electrolytes in the dye-sensitized solar cell and plastic solar cell are under rapid development in solar cell research.

We compare the above results with a technology roadmap that was constructed in Japan by expert-based approach organized by the New Energy and Industrial Technology Development Organization (NEDO). NEDO is responsible for R&D project planning and formation, project management, and post-project technology evaluation in Japan. The Technology Strategic Roadmap (TSR) was developed at the initiative of NEDO and published in 2005. NEDO also developed a fuel cell roadmap and a solar cell, i.e., photovoltaics, roadmap.

The fuel cell roadmap in TSR was published in 2006 and is divided into three categories, i.e., PEFC, DMFC, and SOFC. These three research domains for the fuel cell match the results of our research (Table 2). Our citation network analysis reveals that PEFC, DMFC, and SOFC are the main clusters in

Table 4
Top five clusters in solar cell research

Cluster no.	Cluster name	Keywords	Number of papers	Average year	Growth curve (1970–2005)
S_1	Silicon	a-Si, poly-Si, microcrystalline, efficiency	4634	1995.2	
S_2	Compounds	$Cu(In,Ga)Se_2$, CdS, CdTe, radiation, heterojunction	3481	1998.6	
S_3	Dye-sensitized	TiO_2, Electron transport, dyes, nanoparticles	2267	2003.3	
S_4	Organics	Plastic, polymer, heterojunction, conjugated	1390	2002.3	
S_5	GaAs	$Ga_{1-x}Al_xAs$, junction, Cd(Se, Te), radiation, defects	989	1991.7	

The maximum of the vertical axis is 500 (S_1–S_4) and 200 (S_5).

Table 5
Hierarchical structure of solar cell research

Level 0	Level 1	Level 2	Level 3
Solar cell 13,681; 1998.0	Silicon 4,634; 1995.2	a-Si 1,497; 1997.5	
		High-efficiency cells 1,149; 1997.7	
		Modeling 1,003; 1985.9	
		Polycrystalline 425; 1996.7	
		Limitation and modification of efficiency 369; 2000.3	Theoretical modeling 87; 2001.0
			Effect of impurities and defects 79; 1999.2
			Quantum well solar cells 70; 1999.6
		Heterojunction 112; 1999.8	
	Compounds 3,481; 1998.6	Cu(In,Ga)Se_2 888; 2001.5	Processing and evaluation 302; 2000.9
			Interface and defects 224; 2001.0
			Buffer layer 202; 2002.8
		CdS/CdTe 873; 1998.8	
		Irradiation effects 798; 1993.8	
		$CuInS_2$ 316; 2000.1	
		Textured ZnO 260; 1999.9	
		$CuISe_2$ and other materials 209; 1998.5	
	Dye-sensitized 2,267; 2003.3	Photosensitizer 737; 2002.4	Charge injection, transport, and recombination 240; 2002.6
			New Ru-based dyes 236; 2002.5
			New organic dyes 185; 2001.7
		Electrolyte 715; 2004.2	Gel electrolyte 237; 2004.0
			Nanostructure control 220; 2004.4
			Solid-state dye-sensitized device 166; 2004.1
		Modeling 498; 2003.4	Photocurrent spectroscopy 172; 2003.4
			Mechanism and modeling 172; 2002.7
			Core-shell nanoparticles 113; 2004.5
		Fabrication 205; 2003.5	
	Organics 1,390; 2002.3	Plastic solar cell 448; 2004.6	General 126; 2004.3
			Cell efficiency 108; 2004.9
			Transport and recombination in the membrane 97; 2004.6
			Morphology and performance 79; 2005.1
		Heterojunction 373; 2002.9	Modeling of heterojunction cells 100; 2004.2
			Intermixed structure 80 2002.3
			Doping 74; 2002.2
		Cyanine 328; 1997.0	
		Conjugated polymer 120; 2004.0	

In each column, the name of the cluster, number of papers in the cluster, and average year of publication are shown.

which the number of papers is rapidly increasing. Therefore, the roadmap by NEDO is reasonably to focus on these main emerging domains. But as to the technological details of these clusters, there is some degree of variance. For example, the use of carbon nanostructure to support the catalysts for DMFC is not out of focus in the fuel cell roadmap by NEDO.

As for a solar cell roadmap, NEDO established the Photovoltaics (PV) Roadmap toward 2030 (PV2030) as a long-term strategy for PV R&D in 2004 [31]. In PV2030, the target is the crystalline Si solar cell, which has the highest market share of PV, and also the high-efficiency GaAs-based or $CuInSe_2$ (CIS) solar cell. Dye-sensitized cells were the subject of discussion as seed research after 2010. It was also pointed out that research on dye-sensitized solar cells is focusing on improvement in cell performance to a conversion efficiency of 15% through the development of new dyes and advanced cell structures, as well as the development of production technology for large-area modules with integrated circuits with various substrates. But it missed the technological details of dye-sensitized cells. As indicated in PV2030, the development of new dyes and advanced cell structure research are important topics. But our analysis indicates that research on electrolytes and modeling is under rapid development (Table 4). in particular, Electrolyte including Gel electrolyte, Nanostructure control, and Solid-state dye-sensitized device are rapidly developing scientific topics. The organic solar cell is another emerging domain.

This does not mean that scientific progress in these domains can realize the commercialization of these new cells by meeting market needs, but we take these researches into consideration in order to obtain global data awareness. The citation network approach is a powerful tool to support experts to construct roadmaps in domains where the number and speed of publications is higher than can be handled such as energy research.

4. Concluding remarks

Science and technology for renewable and sustainable energy are indispensable for our future society and economics. To meet the goal of sustainable energy development, there is a growing body of research efforts. The planner of energy research has to grasp the broader coverage of scientific and technological research, and make decisions effective investment in promising and emerging technologies especially with limited resources. Science and technology roadmapping is an activity to build a “consensual articulation of a scientifically informed vision of attractive technology futures” [32]. The computer-based approach is expected to offer supplemental information to construct a roadmap using an expert-based approach.

The aim of this paper is to offer a global structure of energy research and to detect emerging technologies there by using citation network analysis. We tracked emerging research domains in energy research by using citation network analysis. Our analysis confirmed that the fuel cell and solar cell are rapidly growing domains in energy research. We further investigated the detailed structure of these two domains by clustering publications in these domains. Each citation cluster has characteristic research topics, and there is a variety of growth trends among clusters. By using citation network analysis, we can detect and track emerging research domains among a pile of publications efficiently and effectively.

The analysis can offer a concise summary of the overall structure of the target research domain and emerging research topics there. However, we must note that the information obtained by this approach is a summary extracted from a pile of publications, and it discards the most of the information that we can obtain if we actually read the content of all papers. For example, we named the cluster from the titles and abstracts of the twenty most cited papers in the cluster, and therefore missed information from non-cited papers. In other words, we regard papers with fewer citations as not important. But in some situations, such papers might have great potential as innovative technology.

Another shortcoming of this work is on the initial step to construct the corpus. It is not a rudimental task to define a research domain by using queries. For example, if we use “energy” as the query to define the energy research, we overestimate it because of the wide spectrum of its meaning. When we use fuel cell* and solar cell* as the queries to define the research domains, we might underestimate the volume. The method of query selection and expansion to effectively define a research domain is beyond the scope of this paper and leaves an open room for future research.

The last shortcoming of this approach is the existence of time lag. It takes one or two years until a paper receives citations from other papers. It also takes one or two years from the completion of research to the publication of the research. We should complement the shortcoming with other information such as expert’s opinions, because they can sometimes access not-published information via a network of their research community which is sometimes called invisible. For effective roadmapping, the implicit knowledge of experts might be critical in addition to academic publications as an explicit knowledge source. To use experts’ knowledge, we might detect other emerging trends our analysis missed.

While the citation network approach is a powerful tool to visualize the overall structure of research in a manner that an expert cannot perform and to support experts to construct a roadmap, we should use the results as an intellectual basis for constructing a roadmap but not as a roadmap itself. It is a definitely human task to set a vision and draw a backcasting line for present and future actions. According to the definition of roadmap, the analysis supports human experts to obtain a scientifically informed vision of attractive technology futures but does not say anything about consensus articulation.

Acknowledgment

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 18700240, 2006.

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