Examining the dynamics of an emerging research network using the case of triboelectric nanogenerators

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A B S T R A C T

The analysis of a scientist's decision to conduct research in a specific scientific field is an interesting way to trace the emergence of a new technology. The growth of a research community in size and persistence is an important indicator of a new scientific field's vitality. Using a case study on triboelectric nanogenerator (TENG) technology, this study identifies how research participation and community dynamics evolve during the emergence phase of a technology, and further what are the key conditions and determinants of the emergent author network. The study uses scientific publication data from 2012 through 2017 extracted from the Web of Science database. Results show communities emerging through actors' close proximity rather than from their shared thematic orientation. For individual researchers, the boundary between prior research and TENG research was negligible partly questioning the existence Kuhnian paradigm shifts.

1. Introduction

Emergence is what a "self-organizing process produces" (Corning, 2002). Self-organization requires actors, organizations and individuals that will take part in the process of emergence. In the context of technological emergence, the dynamics of actors taking a role in the discovery process have been broadly analyzed. Researchers have studied the emergence of research networks through co-authorship (Suominen, 2014), co-citation (Boyack and Klavans, 2010), and bibliographical coupling (Jarneving, 2007). Researchers have used others studies to examine whether authors share terminology and create persistent new research topics that might be emerging (Guo et al., 2011; Small et al., 2014; Suominen and Toivanen, 2015). In practice, an actor's role has been operationalized through proxies such as the average number of authors per paper, the number of contributing organizations, and the number of countries or cities in which the authors conduct research.

In 1969, Ayres (1969) put forward a framework for the self-organizing dynamic process of actors. This process was based on the number of actors being a function of an already known and interesting idea left within a field. Ayres followed a Humboldtian notion that the progression of technology and selection of research topics are the function of the availability of novel ideas. Ayres drew from Holton (1962), who stated that only a finite lode of interesting ideas exists within a scientific field. Once a scientist opens a new lode via a scientific discovery, more investigators migrate to the new field. This phenomenon is called a 'gold rush' as scholars "defect from their old field, in search for greener pasture" (Ayres, 1969). As the mine empties, making new discoveries more challenging and scarce, researchers are forced to migrate yet again to new opportunities (Ayres, 1969).

It is clear that the issue of researchers pursuing a specific research area is much more complex than the pure Humboldtian endeavor of a researcher (e.g., Laudel and Gläser, 2014). A researcher, particularly so called "normal scientist" transition easily to agendas that are well-funded. (Braun, 2012) Researchers also look for diversity in order to differentiate his or her work from other scientists and mitigate risk associated with a narrow focus. The decision of researchers to endeavor in a field is interesting when assessing the evolution of a technology. Suominen (2013) analyzed the number of entrants in and the cohesiveness of a field by measuring the introduction of new terms. The use of the entrant measure was exemplified in the evaluation of technological progression in two fields: direct methanol fuel cells and dye sensitized solar cells. However, the study was unable to validate further if Holton's (1962) analogy of a finite space holds true.

The discussion on communities and actors is not inconsequential to the broader topic of technological emergence. Emerging technology is defined as a technology that will yield significant benefits for a wide range of economic or societal sectors (Martin, 1995). The characteristics of emergence are novelty, persistence, growth, and community formation (Suominen and Newman, 2017). These characteristics are often translated to scientometric indicators enabling the operationalization of emergence. Templeton and Fleischmann (2013) described emergence as noticeable through the increase in actors over time.

However, existing studies mostly represent the dynamics through networks, such as co-authorship (Perianes-Rodríguez et al., 2010; Glänzel and Schubert, 2005), co-citation (Small et al., 2014), and bibliographic coupling (Kuusi and Meyer, 2007), seldom considering the growth of scholars' participation and its underlying dynamics. Even though the dynamic of scholars' participation is central to Ayres's and Holton's work (Ayres, 1969; Holton, 1962), there are limited studies that quantitatively examine the participation dynamics to track the emergence phenomenon. This study relies on bibliometric data with qualitative information acquired from a survey to explore one dimension of the emergence phase of a technology — how research participation and community dynamics evolve during the emergence of a new technological pathway.

The structure of this paper is as follows: the first section describes the study's background, focusing on the dynamics of emerging scientific communities and their link to the literature on technological emergence. The second part of the background describes triboelectric nanogenerator (TENG) technology as a case study and what the measures are expected to uncover. The third section reviews the data collection process and the methodology, followed by results and discussion in the fourth and fifth sections, respectively.

2. Background

2.1. Emergence in communities of practice

Tracing and conceptualizing the emergence of new technical innovations has always been of interest to scholars, as the innovations are closely linked with economic prosperity (Dosi, 1982). In the past decades, scholars have used different terms and taxonomies to define the phenomena and the origins of emerging technologies. Schumpeter (1961) provided the seminal explanation of emerging technologies. Schumpeter depicted technological development as a circular flow disrupted by spontaneous changes (primarily from innovative entrepreneurs) to the previously existing equilibrium state. Emerging technologies can be the result of either technological development or scientific progress.

The idea of the circular flow in technological change is somewhat analogous with Kuhn's scientific paradigm (Kuhn, 1970). Kuhn introduced the concept of the paradigm shift in the context of scientific discoveries, an act that aligned with the Schumpeterian notion that any progress in science or technology is the result of radical change. Kuhn's view contrasted with the established knowledge of his time – the latter being that the driving force behind scientific advances was a steady accumulation of knowledge and ideas. Kuhn argued instead that the progress of science occurs during a revolutionary explosion of new knowledge, claiming that scientific evolution has a cyclical paradigm. The cycle begins in a stable period of normal science, when research is conducted according to a set of accepted theories among scientific communities. Research endeavors then extend the scope and precision of the established knowledge in the normal science phase, or puzzle-solving phase, which usually has predetermined solutions, pre- cedes a rise in anomalies that violate the "paradigm-induced expectations that govern normal science" (Kuhn, 1970). These anomalies begin to accumulate around certain paradigms, forcing science to explore alternatives, to reevaluate current theories, and finally to shift to a new paradigm. This is similar to Holton's (1962) image of opening a lode.

Paradigm shifts and technological emergence manifest in changes in a given field's communities of practice or dynamism. Dynamism in research communities is mostly analyzed through research collaboration. The motives to investigate collaboratively stem from six factors (Katz and Shapiro, 1994): (1) increased research costs, (2) reduced communication costs and travel costs, (3) advances in science that depend on interactions among scientists, (4) increased awareness of the need for interdisciplinary work, (5) political drivers such as funding, and (6) increased scientific specialization. Collaboration is the core of community creation, as actors share and learn from each other. Scientometric studies have extensively examined collaboration in a number of areas, such as stem cell research (Li et al., 2009), graphene research (Lv et al., 2011), fuel cells (Suominen, 2014), volatile organic compounds (Zhang et al., 2010), and global positioning system research (Wang et al., 2013).

Studies of co-authorship often do not consider the growth of communities, rather explaining differences in existing communities. Ayres described scientific research as comparable to ocean exploration based on the assumption of an ocean comprises a finite pool of ideas. As new research opens new pools to explore, awareness of the discovery spreads, enticing a number of investigators to join in the exploration. As research is conducted, future discoveries become much harder to achieve as most of the finite space has been explored. This results in field saturation, leading to new pools discovered among new streams of science. This process of evolution is illustrated in Fig. 1.

The long dashed line in Fig. 1 describes basic research participation.

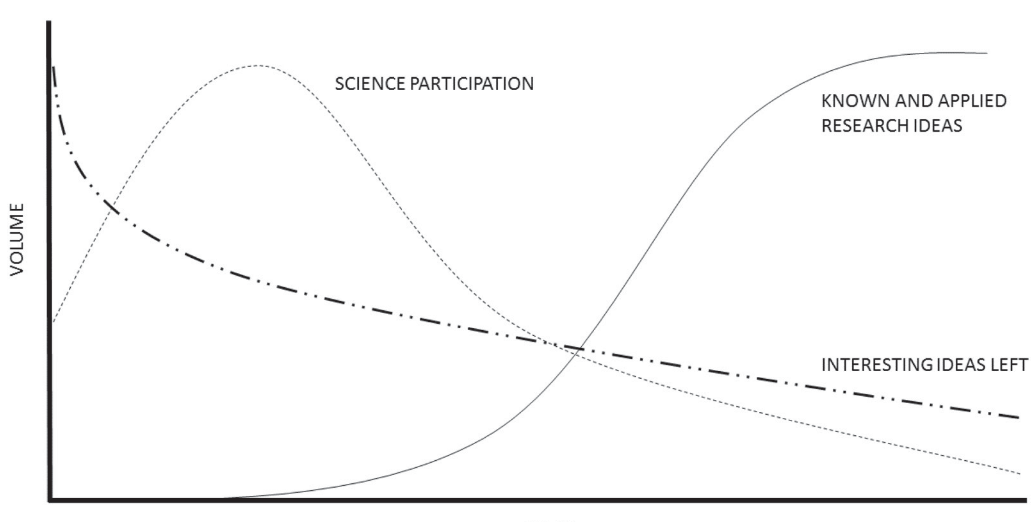

Fig. 1. Ayres's and Holton's model of research evolution (Ayres, 1969).

In Holton (1962), the volume of basic research participation grows rapidly after the opening of a new stream of research. The increase in human labor within the field rapidly increases the amount of already known and applied ideas. The effort needed to find one unit of discovery is higher when less is known about the subject. When almost all the interesting ideas have been discovered, the required effort to produce new known and applied ideas diminishes, resulting in a steeper curve. However, the lack of remaining ideas reduces the volume of research participation. Holton's theoretical framework has remained empirically unexplored. However, understanding how research communities grow and where sub-communities emerge would give much insight to the process of technological emergence.

2.2. *Triboelectric nanogenerator*

To understand how entrant dynamism reveals the emergence of a new technology, the research community growth of TENG technology serves as an example. Invented in 2011 by Z.L. Wang at the Georgia Institute of Technology and first published in 2012 the TENG is a new technology that can effectively harvest ambient mechanical energy from various motions readily available but in a sense wasted in our daily lives, such as human motion, vibrations, mechanical triggering, rotating tires, wind, and flowing water. A nanogenerator comprises two stacked sheets made of materials having distinctly different triboelectric characteristics, with metal films deposited on the top and bottom of the assembled structure. Research has shown TENG technology's promising applications, such as portable electronics and self-powered sensor networks (Fan et al., 2012).

TENG technology has great commercialization potential mainly due to its capacity to harvest energy from the environment. Efforts have been made to explore applications, such as the potential to realize a self-sustaining integrated self-powered microsystem (Zhang et al., 2015), and its low-cost fabrication process (Qiu et al., 2015). Research has suggested that TENG technology can be used as sensors (Alluri et al., 2015), hybrid energy cells (Zheng et al., 2014), portable or wearable electronics (Zhu et al., 2013), or large-scale energy (wind or ocean wave) collection devices (Wen et al., 2014).

Compared to other technologies, TENGs have shown advantages such as high output, high energy-conversion efficiency, as well as abundant choices for materials, scalability, and flexibility. The area power density reaches 599 W /m^2, the volume power density reaches 15 MW /m^3, and the energy conversion efficiency reaches up to 85%. Specifically, the comparison of TENGs with the performances of another mechanical energy harvester, electromagnetic generators (EMGs), demonstrates that the output performance of EMGs is proportional to the square of the frequency, while that of TENGs is approximately in proportion to the frequency. Therefore, TENGs have superior performance when compared to EMGs at low frequency (typically 0.1–3 Hz). Moreover, the extremely small output voltage of EMGs at a low frequency makes them almost inapplicable to drive any electronic unit that requires a certain threshold voltage (≈0.2–4 V). Thus, most of the harvested energy is wasted. In contrast, TENGs have an output voltage that is usually high enough (> 10–100 V) for such an application and is independent of frequency so that most of the generated power can be effectively used to power different devices (Wang, 2017; Zi et al., 2016).

Although the estimation of what represents the metaphorical opening of a lode or the occurrence of a paradigm shift remains highly subjective, and in the case of TENG technology only the future might yield a consensus on its impact, strong evidence exists to support TENGs' paradigm-shifting nature. The inventor, Z.L. Wang, currently ranks first in citations in the field of nanotechnology and nanoscience[1]. He and his research group have received multiple awards, such as the Ente nazionale idrocarburi S.p.A. (ENI) award for the energy frontier. In the ENI press release[2] the committee highlighted TENGs as a completely new group of devices showing significant potential in energy retrieval and generation.

TENG technology is a valuable case study to understand research participation and community dynamics during the emergence of a new technological pathway. TENG research would seem to offer a metaphorical opening of a lode (Holton, 1962) or a Kuhnian paradigm shift (Kuhn, 1970) used as a starting point for this analysis. The technology merges different aspects of natural sciences from materials science (19% of publications), physics (14.1% of publications), chemistry (17.5 of publications). This cross-disciplinarity increases the applicability of the results, but is should be noted that our data does not extend the natural sciences.

3. Data and method

3.1. *Data collection*

Two datasets were used to retrieve information for this study: a scientific publication database and a questionnaire. Publication data was used as a proxy to understand the behavior of research communities in TENG technology. The search query used to obtain the data was formulated via keywords collected and reviewed by TENG experts at the Georgia Institute of Technology. The search was executed in May 2018 and retrieved 1229 records of TENG publications from the Web of Science (WoS) Core Collection database. The search query was limited to the time period from January 2012 through December 2017.

The questionnaire was designed to collect information on why researchers selected to participate in TENG research and from what origins. This allowed to understand the central motivation, which is key in Holton’s (1962) framework. Ayres (1969) explained Holton's framework as follows: that an actor entering research would be motivated by the ease of making new discoveries. The framework also suggests that when no more easy discoveries remain, many researchers find new topics elsewhere. The questionnaire respondents were asked, using open-ended questions, what their motivations to start TENG research were and, if they had considered dropping the research, could they explain why. In addition, the topical distances between researchers who joined together was a focal point for the research. Kuhn's notion that researchers making paradigm shifts are new to the field was also tested through an open-ended question about what researcher were active prior to their TENG research. Furthermore, the questionnaire contained an open-ended question to identify if the respondents could identify communities that had emerged around TENG research. This was used to better understand if vehicles existed to support community creation. Finally, the questionnaire inquired about the researchers' background (e.g., years in research). The questionnaire recipients were 615 authors of TENG publications retrieved from the WoS database. Authors with missing email information were excluded from the survey. The questionnaire is Appendix A.

3.2. *Research participation and uptake measures*

The publication data was analyzed using a Python script, reading the downloaded data from the WoS. The process read the tabulator-delimited files and extracted the author field (AF) for further analysis. The names listed as authors for each publication were separated into single entities: authors. A data structure was formed to give each author a unique ID and organization, a list of co-authors, and a list of used emails.

Organizations were connected to authors in two ways: first, author

[1] http://www.webometrics.info/en/node/198.

[2] https://www.eni.com/en_IT/media/2018/07/winners-of-the-2018-eni-awards-announced.

affiliations that were nested in a C1 field enabled each author to be connected with a specific organization; second, records that did not have a clear determination of author organizations (i.e., no links from the C1 field) meant that only the reprint author was affiliated with an organization.

The AF was also used to link co-authors. For each paper author, the script stored a list of co-authors. If the authors' email addresses were available, each author was also linked to their co-authors' email addresses. The script checked the availability of email addresses and then linked email addresses with the associated reprint authors. If multiple emails were provided, the script examined if the number of emails corresponded with the number of authors. If the number of emails and authors matched, the emails were linked and were expected to appear in the same order as the authors' names appeared. Finally, each author's record was linked to the record's publication years, title, funding origin, and scientific subject category.

The Python script operationalized research community participation with four variables: the number of authors entering yearly, the number of authors exiting yearly, and the yearly count of active authors. The first measure was defined by the number of authors who first published in a given year t. The second measure was defined by the number of authors published in year t who had not subsequently published in the field ($t + n$). This analysis excluded the last two years in the dataset, since the reliable estimations of exiting could not be made so near the end of the time series. The third measure was calculated by counting each author active in the years they entered and exited the field. If an author did not exist on the active author list before the last two years of the time series, then that author was calculated as active from the time of first publication to the end of the time series. The fourth measure was the number of unique authors in a given year. This did not take into account any other values than the amount of unique author identifiers. The difference between the active authors and the authors' yearly count is that the former did not require authors to publish in each year between their first and last publication to be regarded as an active researcher in the field.

3.3. Communities of researchers

To better understand the growth of communities, individual actors were not the only consideration in this study; co-authorship at both individual and organizational levels was considered. The WoS data was sliced based on years and uploaded to VOSviewer software (van Eck et al., 2010). An analysis based on years enabled an investigation of changes in community structure through community formation. Parameters used to analyze data in the VOSviewer were full counting, including all publications, no expectation of a minimum number of citations or publications, and calculations for all authors. In the last stage, authors with no connections to the other scholars or organizations within the dataset were excluded. The results from the VOSviewer were imported to Gephi for network analysis. For each year, basic network statistics were calculated, which allowed for a deeper understanding of network growth.

Communities were also analyzed at the national and organizational levels. Publication records were connected to the communities' associated countries using full counting. Similarly, the yearly organizational-level activities were calculated using the full counting of identified organization names. To understand whether TENG research communities were growing or becoming more dispersed, the Herfindahl–Hirschman Index (HHI) was calculated on a yearly basis for both national and organizational levels. Finally, the development of TENG communities throughout the time series was analyzed at an organizational level. The modularity algorithm (Blondel et al., 2008a) embedded in Gephi was used to uncover TENG research communities from the full data.

Major communities were further examined to determine the geographical and thematic boundaries of TENG research communities. The geographical boundaries of communities were analyzed using Google's geocoding API. Each organization was geocoded to acquire their latitudinal and longitudinal information. Then, the distances between the co-authoring authors organizations were calculated. TENG research communities were scrutinized using *topical concentration* and *physical distance* measurements. Topical concentration was calculated based on distribution of author-assigned keywords using HHI within each major research community. Physical distance was evaluated as the average physical distance between communities.

Finally, topical changes within the whole TENG community were evaluated. Topical change was calculated by extracting terms from abstracts on a yearly basis. Prior to extracting terms, common scientific publication stopwords were removed and n-grams in the abstracts were merged. For each term extracted, a delta value was calculated as the difference of the term appearing at year t and $t + 1$. This topical change value was used to understand the thematic changes within the research community. The important terms from all major communities were qualitatively compared to the overall thematic changes.

4. Results

The absolute volume of TENG research publications has been growing, and we can identify several emergent factors (see Fig. 2). TENG has a clear invention date and first publication date in 2012, which pinpoints the emergence timewise. The analysis of the retrieved WoS data showed a strong increase in publications. Publication volume had increased from approximately 50 publications in 2012, the year of first publications, to a high of 402 in 2017. This increase of 704 % in publication numbers is the product of research uptake and is much higher than the overall growth of scientific publishing, which is approximately 5% per year (Larsen and Ins, 2010). It also suggests a clear persistence, as the technology has already been around for several years.

4.1. Qualitative insights from the questionnaire

Community creation was confirmed via a questionnaire sent to TENG researchers in the beginning of June 2018. During almost three weeks, 41 of 615 researchers responded to the questionnaire. The results derived from survey analysis are presented in Table 1, and the content of the questionnaire is presented in Appendix A. About half of the respondents identified themselves as senior scientists (48.78%),

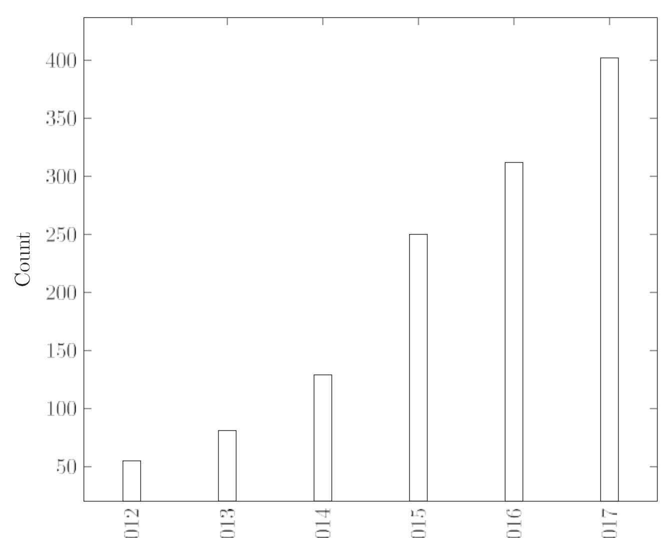

Fig. 2. The yearly distribution of TENG scientific publications from 2012 through 2017.

Table 1
The result of questionnaire.

Research time and duration	Time period (Year)	Number of respondents	Number of respondents (%)	Notes
Involved in research activities	Min (1–5 years)	10	24%	
	Ave (5–15 years)	17	41%	
	Max (more than 15)	14	34%	
Intention to leave TENG research	Yes	2	5 %	The reasons are not reported.
	No	38	95%	
Involved in preparing TENG project for future	Yes	34	82%	
	No	7	17%	
Respondent's current field of research (Cluster number)	Cluster name	Number of respondents	Number of respondents (%)	Notes
1	Energy harvesting material	14	26%	
2	Sensors, self-powered sensors, sensor network analysis	9	17%	
3	Triboelectric nanogenerator (TENG)	9	17%	
3	Other fields	6	11%	e.g. Vascular biology, printed device, vibration, synchrotron radiation techniques, Li-on battery, flexible electronics, automated driving and active safety system.
4	Nanogenerators	4	7%	
5	Micro/nano electromechanical systems (MEMS/NEMS)	4	7%	
6	Piezoelectric electronics	3	6%	
7	Physics	2	4%	
9	Graphene	1	2%	
10	Mechanical Engineering	1	2%	
11	Material science	1	2%	
Motivation factors to engage with TENG	Cluster name	Number of respondents	Number of respondents (%)	Note
1	Potential application in future	26	60%	e.g. Power source for LED light, electronic devices, micro-sensors, wireless sensor networks, wearable display, artificial electronic skin, application Internet of things (IoT)
2	Novelty	6	14%	
3	Personal research interest	4	9%	
4	Promising development trend and current performance	4	9%	
5	Collaboration purposes	2	5%	e.g. Collaboration with specific companies and colleagues within the research communities
6	Other reasons	1	2%	e.g. Engaged because of being in a field of research thematically close to TENG.

which means they have an independent research-and-development position in academia with significant control over research topics. The remaining respondents were at mid-senior- (26.83%) or junior-level (14.63%) positions with partial or no control over their research topics. For industry position the respondents did not have senior-level respondents, but included 4.88% mid-level and 2.44% junior-level respondents. Finally, the respondents included 2.44% holding a emeritus position.

Almost all respondents had affiliated themselves with one or more TENG-related conferences, annual summits, or journals articles. Based on the respondents' answers, the major scientific venues for the TENG research community were identified as the Nanoenergy and Piezotronics International Conference, the Materials Research Society Conference, and the Nanoenergy and Nanosystems International Conference.

Although TENG technology was introduced in 2012, 41% of respondents reported that they had research careers between 5 and 15 years in length, and 34% reported a research career of more than 15 years. Respondents had been engaged with research for 12 years on average. According to Table 1, 95% of respondents would continue their research on TENG and stay in the community. In addition, 82% of respondents were then currently working on or planning to propose research projects with a focus on TENGs.

Respondents active in TENG research had different research backgrounds. Open-ended responses were labeled as 11 categories (see Table 1). It should be noted that each respondent could have been affiliated with more than one cluster. The majority of respondents (26%) were active in the topics of energy harvesting materials. The second and third clusters had a similar rate of affiliated respondents: 17% each. The following research clusters containing less than 10% of responses: nanogenerators, micro/nano electromechanical systems, piezoelectric electronics, physics, graphene, mechanical engineering, and material science in general.

Regarding scientists' main motivations to join the TENG research community, the answers were clustered into six main categories (see the last section of Table 1). "The potential applications of TENG technology in the future" and/or "TENG is a multi-purpose emerging technology" attracted almost 60% of respondents to conduct TENG research. "Novelty characteristic of TENG technology" was the second most important reason why respondents (14%) decided to join the TENG research community. About 9% of respondents reported that personal research interests motivated them to engage with TENG research. Another 9% of respondents identified "the rapid development" and "the current high performance" of TENGs as the motivation for pursuing TENG research. "Building research network" and "Collaboration with industry" were the reasons for only 5% of respondent.

Overall, respondents seemed to associate their TENG research with research they had been conducting for a longer period. This is apparent from the fact that the majority of respondents affiliated themselves with TENG research for a period longer than the technology's invention date. Researchers were engaging with TENGs mostly due to the intrinsic motivation (Lam, 2013) of applying TENGs as a multipurpose technology.

4.2. The research community analysis results

Central to the notion of Holton (1962) was that a new promising field would attract researchers to join that field. The idea further developed by Ayres (1969) claimed that researchers are prone to exit a field if it does not yield results. For TENGs, the results suggest a strong upward trend in the size of the research community, as seen in Fig. 3. By the end of 2017, a research community that began with 200 authors in 2012 has grown to approximately 1500 members by the end of 2017. The growth rate of new researchers joining the field is also significant. While in the first three years, new publishing researchers remained under 300 members, by the end of 2015, nearly 600 new members were doing TENG research.

Author dynamics were calculated through four measures: unique, active, new, and leaving authors (Fig. 3). During the first year of publication, the field already had 261 authors. This is significant if we consider that TENG was invented late 2011 and first published in early 2012. It suggests a rapid migration of researchers from other fields that were thematically close to TENG. This is also supported by our questionnaire results. At the end of 2012, 191 authors left the research area. By "leaving" we refer to the authors who did not publish new research throughout the rest of the time series. This resulted in 73% of authors who did not publish research in any subsequent years. Since then, the number of authors leaving the area have remained relatively stable and much lower than that of new researchers joining the field.

In addition to participation growth in the field, emergence requires some coherence. TENG research is a highly cooperative research area. Co-authorship of TENG publications describes progress of TENG community development. Fig. 4 shows the co-authorship changes throughout the study's period. As seen in the figure, two distinct clusters of researchers are identifiable, both connected by a few central authors but separated by a number of researchers who do not co-author broadly. In the figure, we can also clearly identify the central role of the inventor, see as the largest orange node.

Complementing Fig. 4, the analysis of the yearly network formation for TENGs enables understanding of the area's growth. Network measures are shown in Table 2. The average degree, the average of all author connections with other authors, has remained relatively stable. An author has, on average, four to five co-authors in a given year. Co-authorship is often studied on a paper level, whereas results here focus on the community around a researcher per year. The literature shows that paper-level co-authorship is on average approximately four authors (Glänzel and Schubert, 2004). In this context, TENG research does not differ from other scientific endeavors.

When the author count increases the diameter of the network, the longest path in a network grows as new researchers join at the ends of the network, with limited cooperation within the community. The average path length also increases, which means not only one or two researchers are at the ends of the network, but the overall community is becoming more sparse. Network diameter, the ratio between author connections to all possible connections, also decreases to support the notion of a more sparse community.

One characteristic of emergence is global presence (Rotolo et al., 2015). Although the results of this study indicate that the community has grown in terms of individual actors, they tell little of the community's global growth. In Fig. 5, the global spread of TENG research is evident. The figure shows that while a community is growing by the number of actors, it really is only centered on three countries: the USA, China, and South Korea; all other countries show only modest publication counts. The number of countries with at least one TENG publication has grown from seven in 2012 to 32 in 2017. This development is similar to the findings in the emergence of fuel cell technology (Suominen, 2014), where the number of countries grew linearly. Interestingly, if a threshold of countries with at least five publications is used, as in Suominen (2014), only two countries met that limit in 2012, growing to 10 in 2017. A similar pattern was seen in fuel cell technology.

The connection between authors and countries identified the sparse contributions from all except the core countries. The majority of authors in the dataset were affiliated with an organization based either in China, the USA, or South Korea. In 2012, the number of publications from China increased from 11 in 2012 to 226 in 2017 and the USA increased from seven in 2012 to 120 in 2017. It should also be noted that some authors can have several affiliations, which were whole counted to accredit each mentioned country. Notable increases in the number of publications have taken place in South Korea. While South Korea had just three publications in 2013, in 2017 its publication number had grown to 84. All other countries remained at an extremely

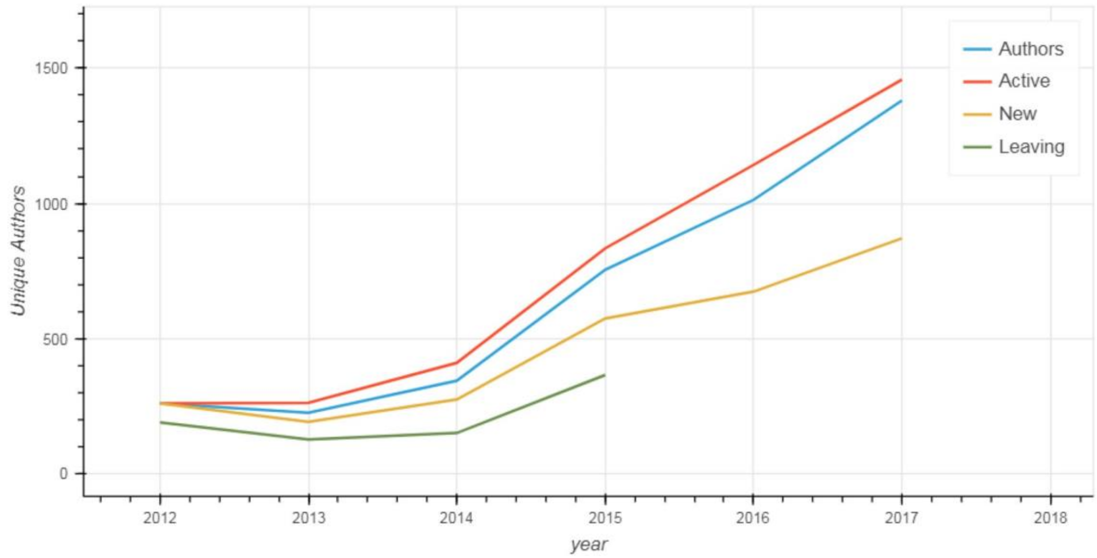

Fig. 3. Size of the TENG research community. The figure shows all active authors, unique authors yearly, new authors, and authors leaving. The time series for authors leaving concludes at the end of 2015, as the calculations were based on an author continuously publishing.

low publication growth rate. Countries such as the United Kingdom and Germany, which account for a significant amount of global scientific production, had less than 20 publications each.

The HHI highlighted the concentration of the scientific community. On a national level, TENG research was significantly concentrated. HHI values had grown from 29% in 2012 to a high of 37% in 2013, and then to 25% in 2017. For comparison, the overall concentration of scientific research is approximately 10% (Veugelers, 2010). Ultimately, although the TENG research community appears to be global, it has actually been concentrated in a small number of countries.

At an organizational level, the Chinese Academy of Sciences and the Georgia Institute of Technology are the core organizations in the field. From 2012 through 2017, these two organizations accounted for nearly 30% of publications, often with researchers sharing affiliations. Comparing the two largest organizations with the rest, it is noteworthy that the 34 next-largest organizations produced roughly the same amount of publications as the two largest. Table 3 highlights organizations with over 20 publications, 2012–2017.

Focusing on the emergence characteristic of global presence, the number of organizations had grown more dramatically than has the number of countries with a significant role. From the start of 2012 to the end of 2017, the number of organizations had grown from 27 to 274, as seen in Table 4.

Using the HHI for organizational authorship, TENG research has not been a particularly concentrated research community, especially when comparing on a national level. Table 4 shows that the field continued to become more concentrated from the beginning of 2012 to the end of 2015, when it began to diminish in concentration to the end of 2017. It is noteworthy that even though the two largest organizations have played a significant role, the increase in the number of organizations keeps the HHI values small. The community formation is visualized by co-authorship network on an organizational level, as seen in Fig. 6. In the figure, strong links are evident between the Chinese Academy of Sciences and the Georgia Institute of Technology seen as the largest green nodes. However, it is worth mentioning the dual position of Z.L. Wang as the central author in Fig. 4; Wang has led the TENG research in both leading organizations. This connection might overemphasize the link between the organizations.

The co-authorship network from 2012 through 2017 was used to evaluate the types of communities formed (as seen in Fig. 6). The communities were clustered using the modularity algorithm (Blondel et al., 2008b). The analysis resulted in 87 communities, among which only four had over 5% of the authors. The largest organizational cluster (17.32 %) was centered in South Korea. The second largest (16.23%) was centered in the two largest organizations, complemented with a number of geographically sparsed Chinese organizations. The third largest community (11.4 %) was a spread of central organizations, with Soochow University contributing a significant portion of the publications. The fourth largest cluster (7.68%) was a mix of North American and Chinese organizations, such as Huazhong University of Science & Technology and University of Toronto. In addition to the large communities emerging, it is significant to note that Fig. 6 shows a number of organizations not connected to the overall community of TENG research (in gray). These organizations remained isolated from 2012 through 2017.

To better understand the communities embedded in Fig. 6, physical distance and thematic concentration of each of the four largest communities was calculated. As can be seen in Table 5, the thematic concentration and physical distance had a modestly negative correlation ($r = -0.44$, $p < 0.05$). The relatively low correlation did not allow for strong conclusions, but the table does clearly demonstrate that in addition to the cluster of authors, new communities grew from regionally bound spaces, such as a community that has a high concentration of South Korean organizations.

Table 6 describes the thematic changes in TENG research overall. The most important terms are centered on the core technology elements. Terms such as “TENG,” “triboelectric,” and “device” remain among the most emergent. The only significantly emergent application on the table is the emergence of sensors and wearable applications.

Concerning different communities, the second community, on which most TENG research is centered including the inventor of the technology, the most frequently used terms were “TENG” or “energy harvesting”. The term occurrence suggests that this community has been focused on the core technology. Other communities around the technology have had different thematic orientations. The first community was thematically concentrated on important terms such as “self-powered sensor arrays” and “silk fibroins.” These terms are highlighted as they are not presented in the other communities. The third community appears to have been specialized through terms such as “self-healing” and “TENGs”. The fourth community was connected through terms such as “in vivo energy harvesting” and “arterial pulse monitoring,” which did not appear in other communities. Interestingly, these differences are not visible in Table 6; they are much subtler. The selected terms are highlighted as they appear in a particular community

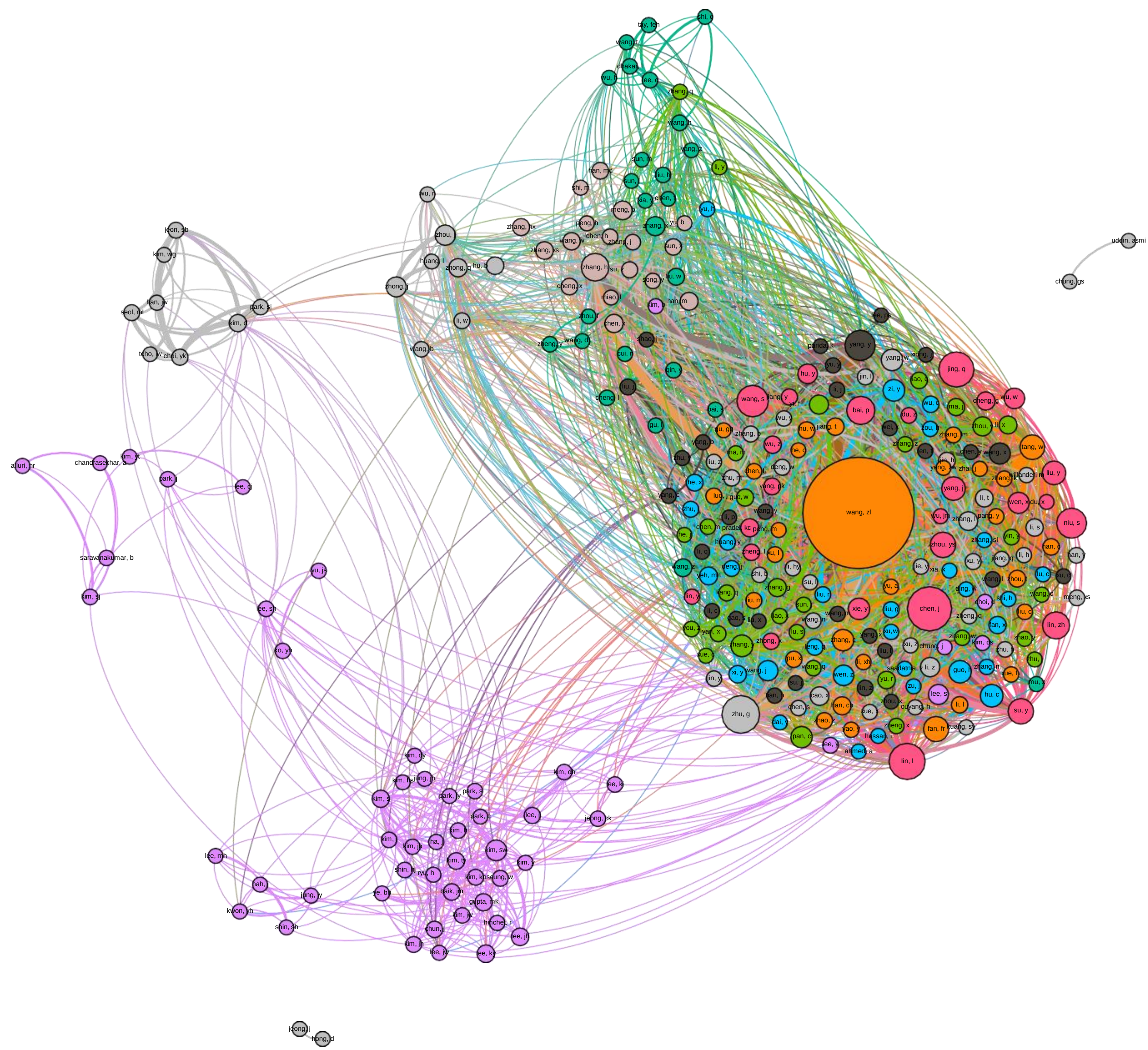

Fig. 4. Co-authorship in TENGs, 2012–2017. Color represents cluster resulting from an analysis done by VOSviewer. The network graph is available online at http://arhosuominen.fi/TENG/author/ and the related datafile at http://arhosuominen.fi/TENG/author/author_TENG.gexf. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Network measures for each year of TENG co-authorship networks.

Network measure	2012	2013	2014	2015	2016	2017
Nodes	91	128	233	568	763	1094
Edges	365	579	1107	2792	3863	5680
Average degree	4.011	4.523	4.751	4.915	5.063	5.192
Network diameter	5	4	5	7	9	9
Graph density	0.089	0.071	0.041	0.017	0.019	0.01
Avg. path length	2.216	2.121	2.709	3.105	3.439	3.682

but are not visible in any other major community.

5. Discussion and conclusion

In this paper, we studied the authorship dynamics of a newly emerging research field — TENG technology. The aim was to find the characteristics of research community development. This is important because studies analyzing technological emergence usually use terms as a measurement, while the theoretical background on emergence would suggest a broader vantage point (e.g. Ayres, 1969). While authors such as Kuhn (1970) focused on the paradigm shift, and more contemporary studies on technological emergence have focused on the characteristics of a technical entity (e.g. Rotolo et al., 2015), a researcher's decision to join an emergent field is central to its emergence and development. There have certainly been studies on researcher motivations (Lam, 2013), but the literature on authors' decisions to join a new research field does not really exist.

In this study, we found that a novel discovery quickly engaged researchers to join that discovery's field. Spreading through the central actors, new scholars joined the research on the periphery of the author network. Within six years, a strong organizational network had

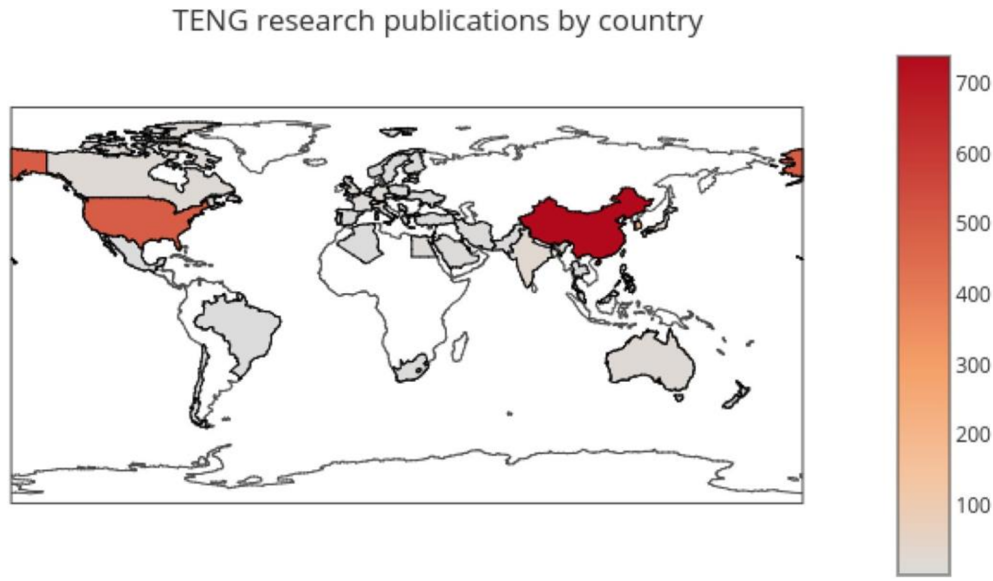

Fig. 5. TENG research publication, 2012–2017, count by country.

emerged, and although the original community can still be identified, new communities have emerged with a significantly stronger regional boundary. Subtle thematic differences are also visible, but overall the field has remained relatively homogeneous. This suggests that community building and the departure from the seed community is driven by localities and not so much by research focus. This is clearly visible within TENG studies, with the exception of medical applications evident for the fourth community identified in this study. In addition, as seen in Fig. 5, the number of organizations on the periphery of TENG research is not linked to any community. Although the four major communities highlighted in this study continually dominated, the modularity algorithm resulted in a total of 87 communities. It remains in question how this many new communities were built on the discovery of TENGs. Holton's (1962) notion of easy research opportunities as the driver for joining a research field should be thoroughly revisited to better understand the motivations of the outlier organizations.

Interestingly, the findings from the questionnaire could yield a partial explanation for the numerous outliers in this case study. Questionnaire respondents reported a significant amount of time in their research careers before shifting their focus to TENGs. This suggests that researchers did not consider changing their field of study when starting research on TENGs; they rather continued existing research through TENGs. This highlights that the researchers were not new to research or to the field, and that arguably, the cognitive distance was minimal between work these researchers had done before TENGs and

Table 4
Organizational count and organizational concentration using HHI.

Measure	2012	2013	2014	2015	2016	2017
Count	27	40	67	117	174	274
HHI	7%	15%	13%	8%	5%	3%

with TENGs. Respondents' perception was that their TENG research had formed a logical continuum with their previous research agenda. This poses a question: Is TENG technology a Kuhnian shift in the paradigm (Kuhn, 1970) or simply a continuation of normal science?

If TENG technology proves to be a paradigm shift, it will take future research to confirm this. Our current findings on the importance of TENGs would support its significance as a scientific breakthrough. Journal citations and numerous awards based on peer-evaluation are significant evidence of its importance. If we accept the TENGs as a paradigm shift or as a metaphorical opening of Holton's lode, we need to better understand the cognitive distance of paradigm shifting discoveries. Based on our findings, paradigm shifts do not require a declaration that the "model is broken" and that the actors pushing the paradigmatic change be new to the field. This forces us to question if the Kuhnian paradigm shift is valid for the current scientific process.

The findings of this study offer a different perspective on the analysis of emergent technology. Besides the most recognized

Table 3
Organizational-level publication counts in TENG research, 2012–2017.

Organization	2012	2013	2014	2015	2016	2017	Total
Chinese Academy of Sciences	4	30	54	77	84	112	361
Georgia Institute of Technology	7	34	58	75	74	80	328
Chongqing University		5	9	18	18	17	67
Peking University		6	8	11	13	18	56
Universty of Science & Technology of Beijing	1		2	13	13	15	44
Korea Advance Institute Science & Technology			2	9	11	17	39
National Center for Nanoscience and Technology					6	31	37
Tsinghua University		3	5	8	9	11	36
University of Chinese Academy of Sciences					5	25	30
Huazhong University of Science and Technology	2	2	2	6	4	7	23
National University of Singapore		1	1	6	8	7	23
University of Electronic Science and Technology of China		3	5	2	7	6	23
Sungkyunkwan University			2	6	9	5	22
Kyung Hee University			2	4	6	9	21

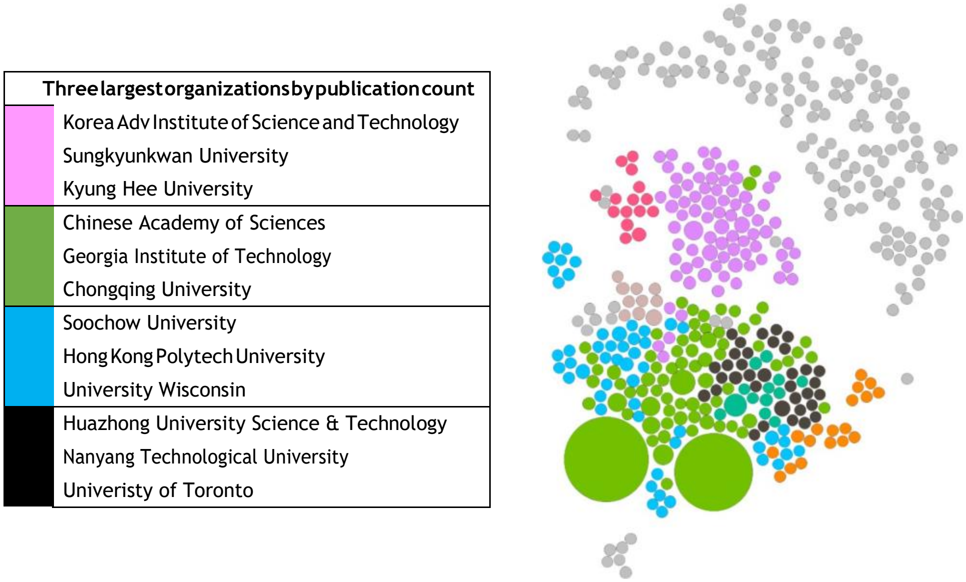

Fig. 6. Organizational-level TENG co-authorship network, 2012–2017. Clustering based on the modularity algorithm (Blondel et al., 2008b). The network graphs is available online at http://arhosuominen.fi/TENG/org/ and the related datafile at http://www.arhosuominen.fi/TENG/org/org_coauthorship_TENG.gexf.

Table 5
The four largest communities in TENG research as measured by thematic concentration and physical distance.

Community	HHI	Average distance (km)	St.dev	*N* (organizations)
1	0.74	3891.40	4891.70	82
2	0.75	6854.46	4236.96	69
3	1.42	4094.62	4236.87	56
4	0.91	5696.92	5297.54	34

characteristics (e.g. Rotolo et al., 2015), we find the need to look at technological emergence through the dynamics of research community formation. Further research is needed to better understand why individual actors make a decision to conduct research in a particular field. While motivational studies (e.g. Lam, 2013) have provided some evidence, using the framework of Holton (1962) as a foundation, we should better understand the selection to opt-in and opt-out of a line of study.

In addition, our results suggest that community creation is local. Even though there is much research on the internationalization of science, our results show that early communities of research would be more local. This could suggest that, at an early stage, research tends to be bound by geographical closeness or similarity. This would be a mechanism of community formation (or departure from the original community). This has policy implications, as it emphasizes the need for the creation of regional policy in supporting emergent technology at an early phase. This could translate into strong regional clusters (Porter, 1998) and/or ecosystem (Oh et al., 2016) policies.

Finally, given the many outlier organizations in this case study, further research on why and how new actors are integrated into communities could yield a better understanding on how locally bound clusters become stable and global. The results suggest that the academic process can communicate interesting results among researchers who can independently adopt these results without collaborative interactions. However, as there are inherent benefits to research cooperation (Katz and Shapiro, 1994; Georghiou, 1998), community formation is rapid after the initial phase. This suggestion has research policy and management implications, as policies should be in place to support integration and community formation where actors identify researchers as outliers in a promising field.

This study is not without limitations. The time series of the data related to TENG publications is rather short. It also only covers the authors' information from 2012 through 2017. Future research can include a broader spectrum of research topics existing in the neighborhood of TENG within or beyond material science research fields. Moreover, this study excluded publications not in the English language; Chinese authors or academic institutes, for example, might prefer to publish in the Chinese language via national journals. It is also worth considering other scientific publication databases besides the WoS, since the proliferation of WoS-indexed publications by Chinese authors within a specific field or time period can be the result of reward incentives provided by governments. In addition, the sample of questionnaire respondents' could have been increased with a longer response period. Although sending reminders to prospective respondents,

Table 6
Terms with the highest delta between years via the frequency of term occurrence in abstracts.

	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017
1st	TENG (121)	TENG (61)	TENG (169)	TENG (190)	TENG (243)
2nd	Energy (44)	Energy (54)	Energy (114)	Triboelectric (65)	Energy (164)
3rd	Triboelectric (31)	Power (30)	Power (102)	Efficiency (34)	Power (95)
4th	Device (20)	Motion (27)	Device (83)	Surface (33)	Triboelectric (71)
5th	Voltage (20)	System (24)	Triboelectric (75)	Stretchable (31)	Sensor (69)
6th	Mechanical_energy (19)	High (23)	High (62)	Frequency (30)	Wearable (66)
7th	Effect (17)	Water (23)	Voltage (51)	High (30)	System (61)
8th	Current (17)	Sensor (20)	Sensor (51)	Device (29)	Self-powered (60)
9th	Power (17)	Electric (19)	Flexible (50)	Electrical (27)	Surface (58)
10th	Technology (16)	Contact (18)	System (50)	Hybrid (24)	High (58)

targeting prospective respondents in conferences etc. could have yielded a broader sample. Finally, to ensure generalizability, there should be replication studies conducted to better assess the impact of the technologically bound sample used in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2018.10.008.

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