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Tech mining and semantic TRIZ combination for a systemic assessment of technologies. DSSC as case study

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Abstract

In the competitive business environment, early understanding of the dynamics of technology change is crucial to help policymakers and managers make better-informed decisions. Bibliometric analyses have helped in studying trends and technological evolution. Bibliometric analyses have been enhanced via tech mining (text analyses of science and technology information resources). However, more often than not, such analyses focus on a specific technological area, resulting in mainly forecasting incremental advances. The analysis of the interconnected dynamics of technology change warrants new approaches for identifying technology emergence, technological substitution, and the influences of vital socio-economic forces. In this line, this paper introduces a new approach that combines tech mining and semantic TRIZ applied to Dye-Sensitized Solar Cell (DSSC) technology as a case study. This methodological combination brings broader insights to DSSC emergence in conjunction with related technologies that affect its progress, enriching the empirical characterization of the associated technological progression.

Keywords:
Analysis of emerging technology, systemic analysis, bibliometrics, tech mining, semantic TRIZ, SAO functional systemic mapping, dye-sensitized solar cells

1. Introduction

Analyses of emerging technologies can be composed of several forms. Competitive Technical Intelligence (CTI) seeks to inform technology ("tech") management about "who's doing what, when & where." Technology forecasting adds a critical future dimension to gauge likely tech changes. Technology assessment investigates the "unintended, indirect, and delayed impacts" of possible tech changes. The analytical literature on such tech analyses has grown dramatically – a review of 50 years of *Technological Forecasting and Social Change* contributions shows some 50 papers per year through 2006, jumping to over 300 per year in the next decade (Sarin et al. 2019, in process).

Bibliometric tools that tally R&D literature and/or patent activity patterns contribute strongly to empirical analyses of Science, Technology & Innovation (ST&I). Bibliometrics have been enriched by the use of "tech mining" – text analyses of ST&I information resources (Porter and Cunningham, 2005) to extract additional usable tech intelligence.[1] However, more often than not, such tech analyses focus on a specific area of analyzed technology and select components. This within-domain focus leads to a silo effect that limits profiling technological emergence, identification of possible synergistic interactions with other technologies, and vital socio-economic forces at play.

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[1] Annual conferences on *Global Tech Mining* advance this literature – see www.gtmconference.org.

Challenges arise in seeking to treat tech emergence in conjunction with vital contexts. Huang et al. (2015) acknowledge that in the case of emerging technologies, the terms related to a particular technology may not be uniform across players or time, making the search and the integration of scientific reviews more difficult. Moreover, terminological variations across tech domains are often found.

By contrast, systemic innovation approaches focus on systems instead of on particular tech components, thereby addressing analyses from a more complete perspective. The seminal work of Bertalanffy (1970) introducing the general systems theory shows that considering technologies and products as systems –i.e., a set of components, the configuration of parts, and relationships among components and system architecture– leads to a better comprehension of their progress. Altshuller (1984) explains that all technologies exist as a set of components organized to accomplish the main function, and sets the analysis of "technologies as systems" as the starting point of TRIZ methodology. As Bertalanffy (1970) points out, to deal with complex sets, or 'systems,' one should consider aspects related to their number (quantity, citations, repetition, appearance...), but also their type and the relations of their constituent elements. Sahal (1976) also recognizes the need to address different parameters to assess the progress of technological devices. In this line, Dong and Sarkar (2015) highlight the relevance of analyzing the knowledge embodied in the configuration of parts and sub-systems of a product as a way to better measure the progress of complex technologies.

The advantages of assessing technology progress using a systemic approach are well known, and many works can be found putting this concept into practice. Yoon and Park (2005) combined tech mining with morphological analysis for the study of a particular technology, taking into account different parts or constituents, though not analyzing their interactions. Koh and Magee (2006, 2008) analyze a functional classification of elements contributing to any technology; however, the authors list such relationships as a table without detailed parameter interaction description or technology progress assessment for the elements. Moon et al. (2005) propose a useful representation scheme for a technology based on the components and their functioning relationships using a "tech-specs" concept ontology. Such representation introduces a hierarchy of components, mainly by layers more or less proximal to the whole artifact or technology. However, and despite these relevant contributions, many experts acknowledge the need for new techniques and procedures capable of analyzing technology architectures more comprehensively and systemically (e.g., Cunningham, 2009). In this sense, a broader interrelated framework is necessary to understand technological progress better and, thus, to be able to measure it (Dong and Sarkar 2015; Rivkin and Siggelkow 2007; Zhang et al., 2014). Yu et al. (2013) propose a functional representation to assess the utility of any technology, extracting the parameters. In this line, Brian Arthur (2011) explains the birth of technologies as new combinations of existing components, showing new functionalities deriving from such new architecture or a new combination of technology components. Thus, the need to assess technologies taking into account their configuration, their component architecture and interrelationships, and their relationship with external elements along a technological evolution curve seem vital for effective analysis of emerging technologies. In this context, our first research question is as follows:

RQ1. Can TRIZ functional analysis, complemented with a syntactic-semantic TRIZ-based tool, improve the systemic analysis of a given technology by helping assess its components configuration and architecture?

Identifying potential changes in technology and its corresponding environment, environmental scanning (akin to CTI), is a method that systematically surveys and interprets relevant data to identify events, trends, issues, and expectations. However, environmental scanning generally follows a linear model of innovation, from scientific discovery, through technological development in firms, to the marketplace (Martino, 2003). Such a model does not adequately take into account open innovation (Chesbrough, 2006). Open innovation facilitates a given technology progressing by introducing advances from other technologies. In this line, analyzing the role played by each component in other technologies allows identifying the key parameters that track technological progress (Koh and Magee 2006). In this sense, the use of mereology relations via text Subject-Action-Object (SAO) text analyses (Bachilo et al., 2006) enables linking components to different technologies, showing the possible interaction of other technologies in the pace of progression of a component of a given technology. In this line, Giordano and Fulli, (2012) and Adner and Kapoor (2016) suggest the analysis of an entire ecosystem of a given technology to better find solutions and predict its outcomes. Such analysis leads to our second and final research question:

RQ2: Can semantic TRIZ help to explore the interaction of other technologies in the pace of progression of key components of a given technology?

To approach the aforementioned research questions, the present work offers a procedure to analyze Dye-Sensitized-Solar-Cell (DSSC) technologies systemically. The relevance of sustainable energy sources for reversing climate change is moving research to find new materials and new architectures for attending such need. Among these, DSSCs are notable as cheap and emerging photovoltaic technology (Kozma and Castellani 2013; Li et al. 2019; Iqbal et al. 2019). The proposed procedure allows analyzing DSSC trends with a combination of tech mining and semantic TRIZ (Vicente-Gomila and Palop 2013). Initially coined by Verbitsky (2004), semantic TRIZ is seen here as the application of syntactic-semantic mining tools to ST&I information, informed with the knowledge of the TRIZ methodology and technological innovation processes. The combination of approaches – tech mining and semantic TRIZ – provides fresh insights to understand tech evolution and behaviors.

Semantic TRIZ helps to identify the hierarchy of principal components, as well as auxiliary components and interrelationships among them. Complementing this information with tech mining enables us to assess the progress of components and their functions. Tech mining can help track tech progress. The tech mining/TRIZ combination can help identify critical parameters to track technological progress (e.g., along with logistic "S-curves") (Koh and Magee 2006). Here, we use the combination to help illuminate the systemic analysis of DSSC technology, expanding the initial scope of a technology to understand tech progress vis-a-vis shifts to other developing technologies better. In this case, the devised procedure aims at finding strategic implications for the hierarchy of DSSC technology components, as well as for its immediate ecosystem, providing a robust framework for analyzing and forecasting its further evolution.

2. Material and methods

The approach presented in this paper covers the following four steps:

1) Review of the state of the art of DSSC technology.

2) Functional analysis and mereology to identify the main technology components, systemic model definition, and expert validation.
3) Application of tech mining to create a list of factors and to obtain comprehensive citation trends of each component of the systemic model.
4) Role exploration of each component in other technologies using semantic TRIZ.

2.1. Review of the state of the art of DSSC technology.

The first step is to construct the literature corpus about DSSC technology by formulating a retrieval strategy in scientific literature and in patents. The retrieval strategy should use all possible synonyms and should be considered open, in the sense that further application of the methodology will expand or filter the literature corpus later.

After search and retrieval, tech mining was applied, following the nine steps of the decision phases and the tech mining process (Porter and Cunningham, 2005), to analyze the state of the art and trends of the different tech components of the DSSC system. The research publication search strategy built on previous bibliometric analyses of DSSCs (Ma et al., 2014) and was conducted in Clarivate's Web of Science (WoS) Core Collection. The WoS indexes included were: Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index- Science, Conference Proceedings Citation Index- Social Science & Humanities, Book Citation Index– Science, Book Citation Index– Social Sciences & Humanities, Emerging Sources Citation Index, Current Chemical Reactions Expanded, and Index Chemicus. The patent search was performed in the PatStat database using the same strategy. In all cases the materials compiled cover a time span from 1991 to 2018.

In addition, relevant reviews of the DSSC technology were analyzed. These reviews were studied in detail to identify the main DSSC research areas, existing limitations, and future areas of research.

2.2. Functional analysis and mereology to identify the list of the DSSC technology components, systemic model definition, and expert validation.

The second step takes advantage of the TRIZ functional analysis, complemented with a syntactic-semantic TRIZ-based tool and its mereological capability. According to Stanford (https://plato.stanford.edu/entries/mereology/), mereology is the theory of studying relations between parts to the whole and the relations between parts within a whole. The objective is to draw an interrelated SAO Chain model of a given technology. SAO stands for Subject-Action-Object; usually, Action-Object is considered as a 'problem,' where 'S' is a solution to such a problem. Specifically, this approach takes into account the S-A, the element performing some action, and looks to different objects where said action can be applied.

The SAO chain model consists of a basic concept of a group of related elements conforming to a system, in which each arrow points from the 'tool' or function-donor to a function-receiver or 'object.' It represents a function or an action in which the 'tool' changes, controls, or maintains some parameter of the 'object' (Savransky, 2000; Litvin, 2005; Vicente-Gomila, 2009, 2014; Choi et al., 2012).

To establish the hierarchy of the components, one should assess which component is the tool of the system and which components are auxiliary. The tool and the closer to the tool components receive a higher position in the hierarchy.

Once we identify the hierarchy of components, the obtained systemic model has to be validated with expert judgment and literature investigation, to identify main functions and current limitations (Nazeeruddin et al., 2011; Chun-Pei et al., 2013; Longo and De Paoli, 2003). In the present case, the authors contacted the team of Nazeeruddin and Grätzel in Switzerland, leading experts in DSSC development, who reviewed and validated the functional model in an iterative process.

The SAO model helps to understand each component's role, function, and its possible usefulness in other technologies. It helps to explore the functional relationships among the most relevant components, implications of the hierarchy of components of DSSCs, as well as its immediate ecosystem, to offer a model for analyzing the evolution of technologies.

2.3. Application of tech mining to create a list of factors and to obtain comprehensive citation trends of each component of the systemic model

Once the components have been identified, as well as their role in the system and ecosystem, the following step is to explore the research activity on each component. To accomplish this we performed tech mining on the outlined DSSC system. Once the records of a target dataset are mined, the list of terms is extracted from titles, abstracts, and keywords, following the nine steps of the decision phases and the tech mining process (Porter and Cunningham, 2005). By means of natural language processing (NLP) logic, the terms related to the components of the DSSC technology are extracted. The NLP analysis of those terms allows us to group, refine, and "clump" (consolidate closely related term variants) them. This processing yields a list of reasonably consolidated terms. We use those processed terms to analyze the trend for each component of the systemic model. This step should show associations of the role of each component and the hierarchy, as mentioned in Section 2.2. By plotting the NLP extracted terms against time, then we should obtain a comprehensive set of citation trends for the main components of the technology.

2.4. Exploration of component roles in different technologies using semantic TRIZ

The fourth step is to explore the progress of component technologies in other areas. We seek to clarify the components' relationships and hierarchy, and pertinent architecture. By exploring other applications where the component is being used, as well as their research trends, we can compare with its original application. This may show differences that could explain why some components advance faster, and what alternative systems are competing/collaborating. Auxiliary searches can help understand component trends and relationships. At this stage, expert review is precious to check the empirically generated findings. In this line, using semantic TRIZ, through semantically analyzing records of the patent documents with application dates from 1991 to 2018, we extracted the SAOs related to the different components. In this case, we use the mereology SAOs (Bachilo et al., 2006) capable of linking components to different technologies.

3. Results

3.1. *Result of the state of the art of DSSC technology review*

The search strategy in Clarivate Web of Science core collection brought 23,583 abstracts of articles up to 2018. A similar search in PatStat, considering only applications up to 2018, brought 13,416 patent applications, which were also analyzed. The strategy followed and the number of articles obtained are depicted in Table 1.

Table 1.

DSSC search strategy and Data Recovery

#6 23,583 #4 OR #3 OR #2 OR #1 *DocType=All document types; Language=All languages;*
#5 23,100 #4 OR #2 OR #1
#4 1,801 TS=((((dye-photosensiti*) or (dye same photosensiti*) or (pigment-photosensiti*) or (pigment same photosensiti*)) same ((solar or photovoltaic or photoelectr* or (photo-electr*)) same (cell or cells or batter* or pool*))) not (melanocyte*or cancer*)
#3 1,293 TS= ((((dyeadj (sensiti* or photosensiti*)) and (conduct* or semiconduct*)) same alectrode*) and electrolyte*) not (waste-water or wastewater or degradation))
#2 10,439 TS=((DSSC or DSSCs) not ((diffuse cutaneous systemic sclerosis) or (diffuse cutaneous ssc) or (diffuse ssc) or (distributed switch and stay combining) or (distributed static series compensat*) or (decoupled solid state controll*) or (active diffuse scleroderma*) or (systemic sclerosis) or (diffuse scleroderma) or (deep space station controller) or (data storage system center) or (decompressive stress strain curve) or (double-sideband-suppressed carrier) or (flexible AC transmission system*) or (dss induced chronic colitis) or (dynamic slow-start) or (dextran sulfate sodium) or (disease or patient* or QSRR)))
#1 22,853 TS=(((dye-sensiti*) or (dye* same sensiti*) or (pigment-sensiti*) or (dye same sensiti*)) same (((solar or photovoltaic* or photoelectr* or (photo-electr*)) same (cell or cells or batter* or pool*)) or photocell* or (solar-cell*)))
#2 AND #1 10,915
#2 78,292 TS= (perovsk*)
#1 201,342 TS=(((solar or photovoltaic or photoelectr* or (photo-electr*)) same (cell or cells or batter* or pool*)) or photocell* or (solar-cell*))

Table 2 shows the number of WoS publication records and instances found for the more cited components of DSSC technology (instances count each occurrence so that some records contain more than one use of the appropriate terms). Dyes, electrolytes, and counter-electrode are critical components for the improvement of DSSC efficiency (Li et al., 2019). These components are also standard both in rigid and flexible DSSC architectures.

Table 2.

Literature citations of the different DSSC components

Components	# Records	# Instances
Dyes in photoanode	15740	54788
Electrolyte	5412	11891
Photoanode	3319	6091
Counter electrode	3175	5451
FTO Glass substrate	832	1220

Relevant reviews of the DSSC technology were analyzed to identify current trends and limitations or bottlenecks. The need for cleaner and sustainable technologies is increasingly relevant due to the limitation of fossil fuels and the effect on climate change (Singh and Koiry, 2018). Solar energy is one of the increasingly present renewable energy sources (Boschloo, 2019). Due to its low cost and relative efficiency, DSSC has been the motivation of many researchers. O'reagan and Grätzel (1991) invented its current architecture. The DSSC uses a photovoltaic material, TiO2 with a sensitized photo-material, the dye, a counter-electrode, and an electrolyte (Bhand and Salunke-Gawali, 2019). It is of the type of photoelectrochemical cell. Since 1991, researchers have been trying different materials and configurations or architectures, to increase its efficiency while maintaining its low cost. In the case of the sensitized dyes, researchers have intensely searched for materials with light-harvesting capabilities.

The analysis of reviews bring trends and limitations for the key components of DSSCs. The cited reviews explain current research efforts in electrolytes and the search for solid, liquid and mixed alternatives for counter-electrodes, and dyes (e.g. Rahman et al., 2014; Deb Nath and Lee, 2019; Ahmed et al., 2018). For instance, in the case of electrolytes, according to Bella and Bongiovanny (2013), liquid electrolytes are preferred to solid electrolytes due to better electron/ion mobility. However, liquid electrolytes face several limitations. Among these liquid electrolytes, room temperature ionic liquids (RTIL's) offer low volatility and better stability, but on the other hand, they have a drawback in their relatively high viscosity.

In the case of electrodes and counter-electrodes, platinum continues to be the material of choice; however, due to its cost, researchers try to reduce the amount by using only a thin layer of it. (Ahmed et al., 2018). Such an electrode with a thin layer is obtained by sputtering of a platinum thin layer to use the minimum possible amount of platinum yet to have good performance (Selvaraj et al. 2018) (Li et al., 2019).

Dyes, being one of the fundamental components, receive much attention in research and many alternatives are being used with organic alternatives progressing against inorganic alternatives

(Błaszczyk, 2018; Urbani et al., 2019). Finally and regarding DSSC efficiency, the inclusion of ruthenium salts in the sensitized-dye in 1991 (O'Regan and Grätzel, 1991) brought a breakthrough with an energy efficiency of about 10 %. Almost 20 years of research have been dedicated to using Ruthenium salts (Gong et al., 2017). Years after, again a shift of the sensitized dye (Yella et al., 2011; Kannan et al., 2013; Bignozzi et al., 2013) by using P-porphyrin in 2012, brought a 12 % efficiency. In 2013, using perovskite brought a new breakthrough, reaching 15 % efficiency (Upadhyaya et al., 2013). Further work with perovskite and phthalocyanines brought even higher values of 17.5 % efficiency (Cho et al., 2017, Gong et al., 2017; Bhand and Salunk-Gawali, 2019).

The upcoming involvement of artificial intelligence in finding materials combination and alternative architectures in matter of days instead of months (Science magazine doi:10.1126/science.aba5361) may bring new perspectives for analyzing such innovation models.

3.2. *DSSC technology components and systemic model.*

Components of DSSC technology and the SAO chain systemic model can be seen in Fig.1. The blue arrows represent useful functions, whereas the red ones are undesirable functions or shortcomings of the current system. (Arel et al., 2002)

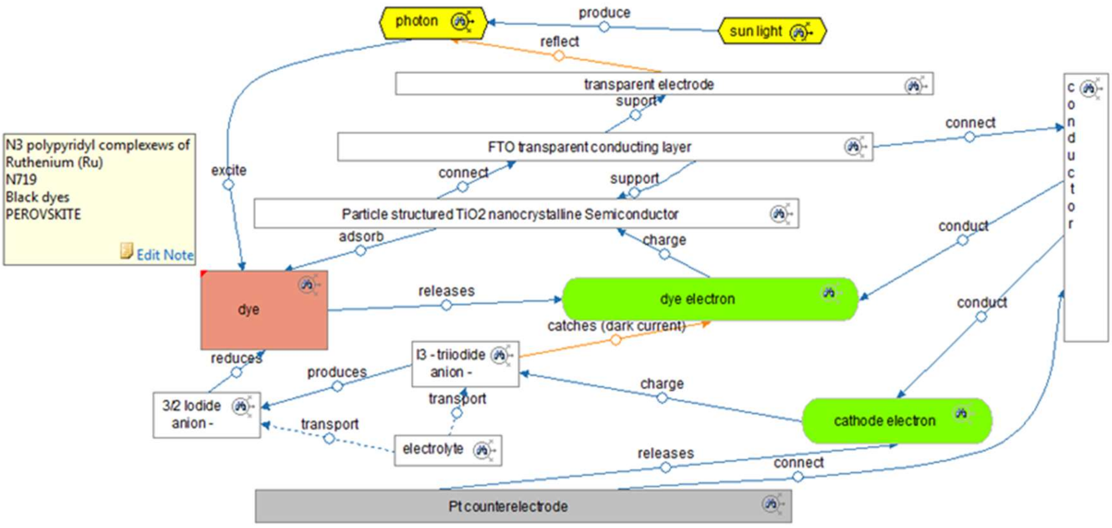


Fig. 1. Systemic DSSC model

The DSSC system illustrates the main components of the DSSC: iodide anions, the electrolyte, the TiO2 nanocrystalline semiconductor, the FTO conducting layer, the transparent electrode, both anode and cathode, and the dye. It also illustrates the functions. It is the 'dye' that acts as the key 'tool' of the DSSC system, producing the energizing electrons. The interrelated systemic SAO chain also shows current limitations – e.g., the dotted line from the electrolyte 'moving' the anions, to represent the need for insufficient speed of the anions.

The hierarchy of the DSSC system components and the relevance of elements acting as 'tools' of the system likely imply different impacts on their progress through the next steps. Knowledge about the interrelations among the DSSC components should help to identify research challenges and bottlenecks of the entire DSSC system.

3.3. List of factors and citation trends of each component of the systemic model.

Terms were analyzed with the tech mining tool, grouped by fuzzy logic and manual touch-up, and classified in clusters. Figures 2 to 10 show the citation results. This helped to associate terms to the components of the technology, to analyze their state of the art and trends.

The analysis of the counter-electrode, due to its relevant contribution to the overall efficiency of the DSSC system (Li et al., 2011; Chen and Shao, 2016), is shown first. Figure 2 represents the frequency of occurrence of terms and the aggregated values associated with two major counter-electrode types based on analysis of the 23,583 WoS articles.

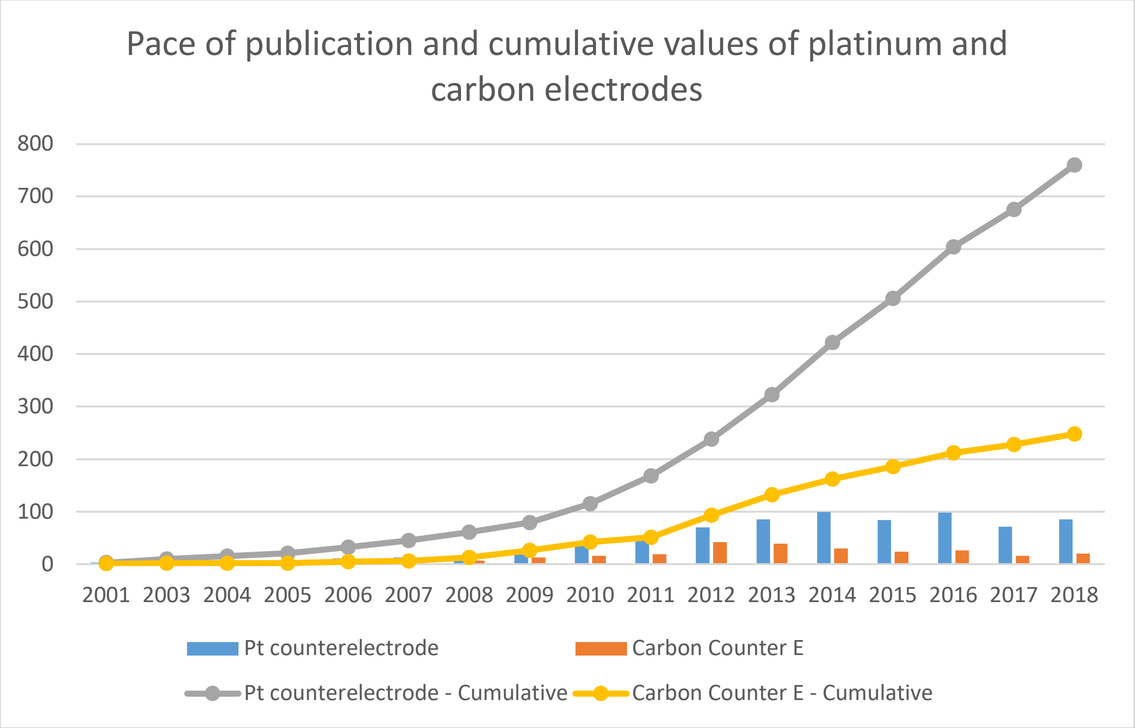


Fig. 2. Pace of publication and cumulative values of platinum and carbon electrodes.

The parallel trend of both counter-electrodes, carbon, and platinum, may be explained as the search for less expensive alternatives. However, the platinum counter-electrode continues to be the element of choice (Ahmed et al., 2018), and its research seems concentrated in reducing the necessary amount of platinum, without losing efficiency. Notice a slow increase in the counter-electrode citation among all the 23,583 DSSC articles in time, as shown in Fig 3.

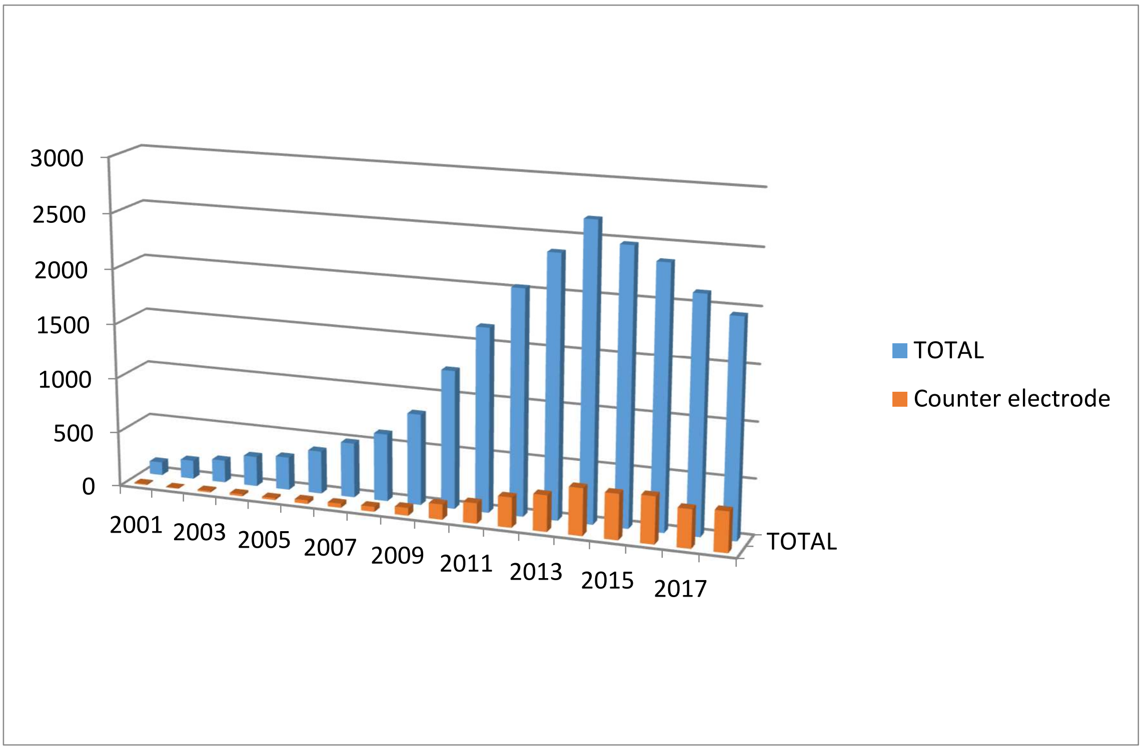


Fig. 3. pace of citation of “counter-electrode” in the total number of articles about DSSC.

The next DSSC component to be analyzed is the electrolyte. The electrolyte is responsible for transporting the ions from the counter-electrode to the working electrode and vice-versa. It is one of the components with limited functionality. Figure 4 shows the pace of citation in the research articles from 1991 to 2018 for the different types of electrolytes used. Figure 5 compares the citation of the types of electrolytes in DSSCs and the total published articles analyzed. A slower pace of citation can be noted contrary to the general trend about the DSSC system.

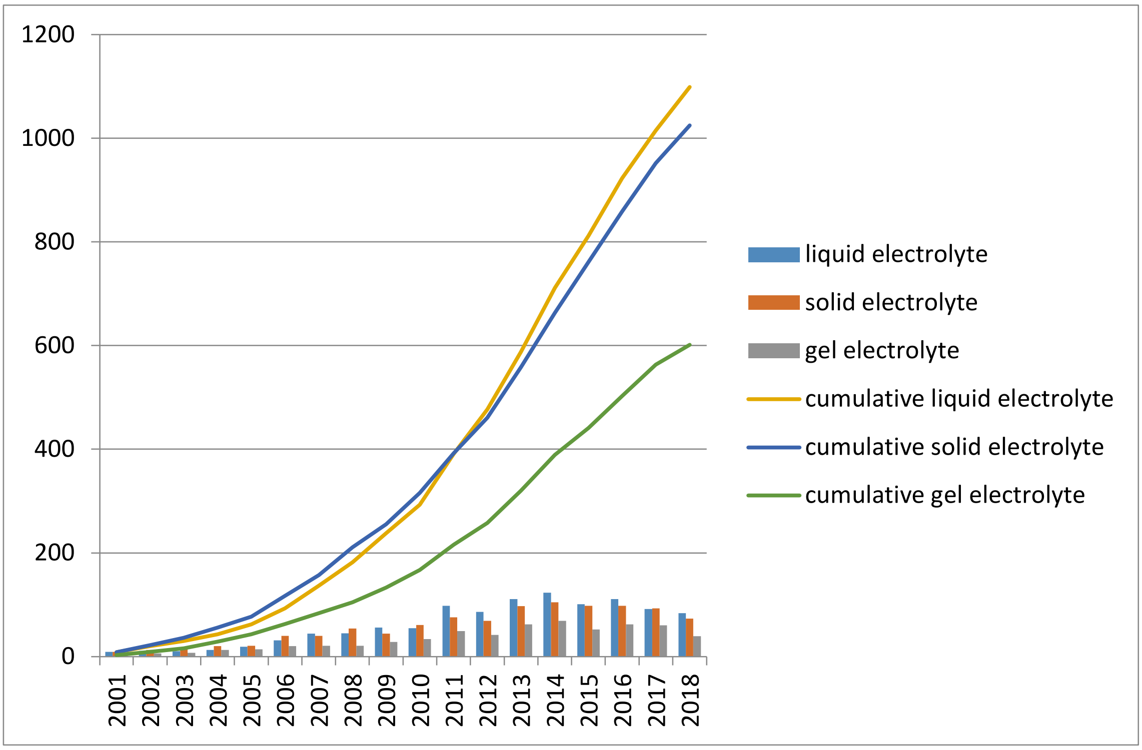


Fig. 4. Pace of citation and cumulative values of different electrolyte types.

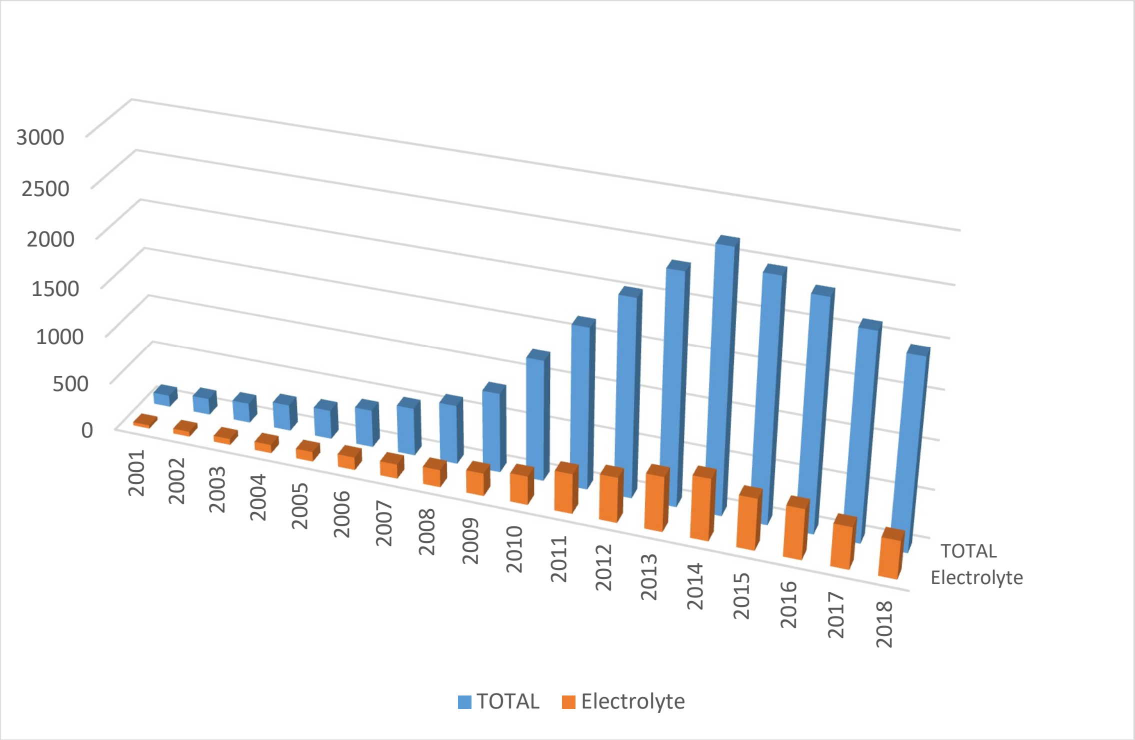


Fig.5. Comparative pace of electrolyte citations and total number of publications.

Figure 6 shows the pace of publications citing activity on sensitized dye. Comparing Fig. 6 to Fig. 3 and Fig. 5, there is a more pronounced pace of publications citing activity on sensitized dye. This fact explains the relative concentration of research activity on the ‘tool' of the DSSC system, as expected. Any change in the 'dye' brings more impact than changes in other components of the DSSC system (Grätzel, 2011) (Jun et al., 2013) (Popoola et al., 2018).

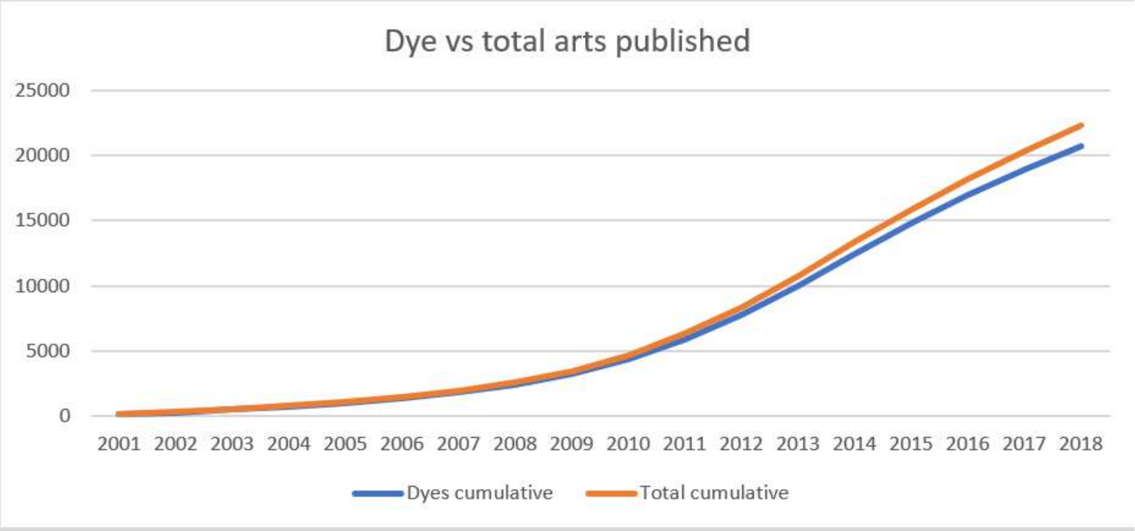


Fig. 6. Cumulative citation of sensitized dyes

Finally, Fig. 7 compares cumulative trends of electrolyte, counter-electrode, and dyes. It depicts, as aforementioned, the leading edge in the citation of the component dye – the tool of the system – versus counter-electrodes and electrolytes – auxiliary components responsible for transporting ions.

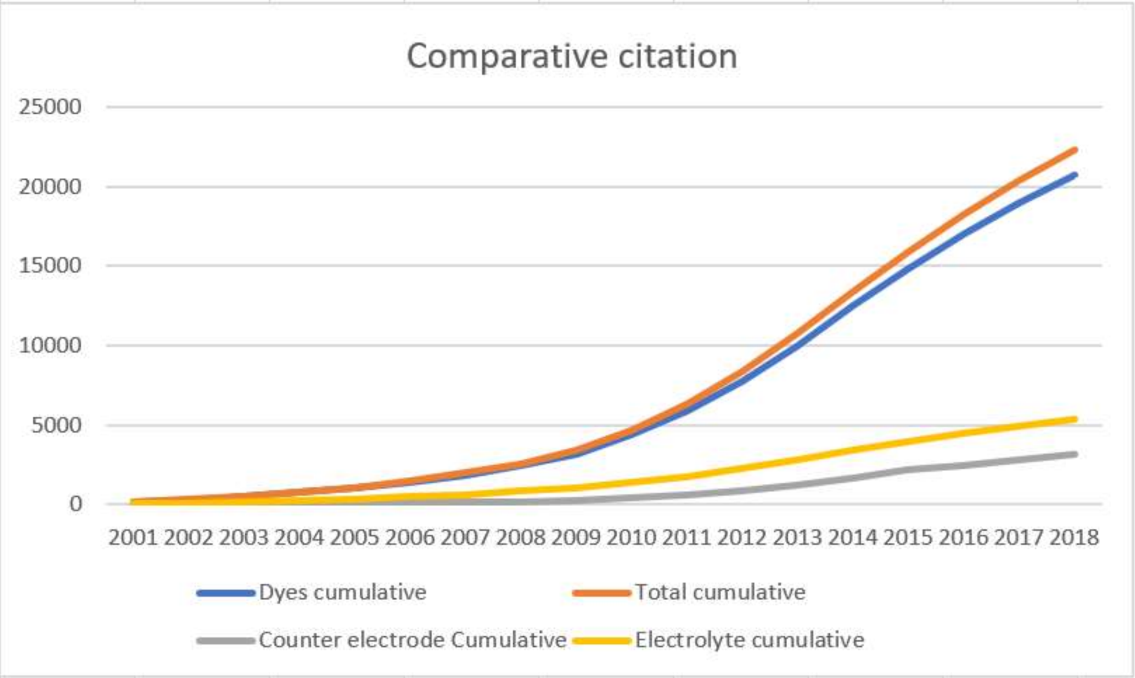


Fig. 7 .Comparative literature citation of counter-electrode, electrolyte and dye.

As the results show an intense research activity in dyes, we have further analyzed the type of dyes, distinguishing between organic and inorganic. Figure 8 shows a higher citation in organic dyes due to their lower price, higher availability, and more environmental friendliness.

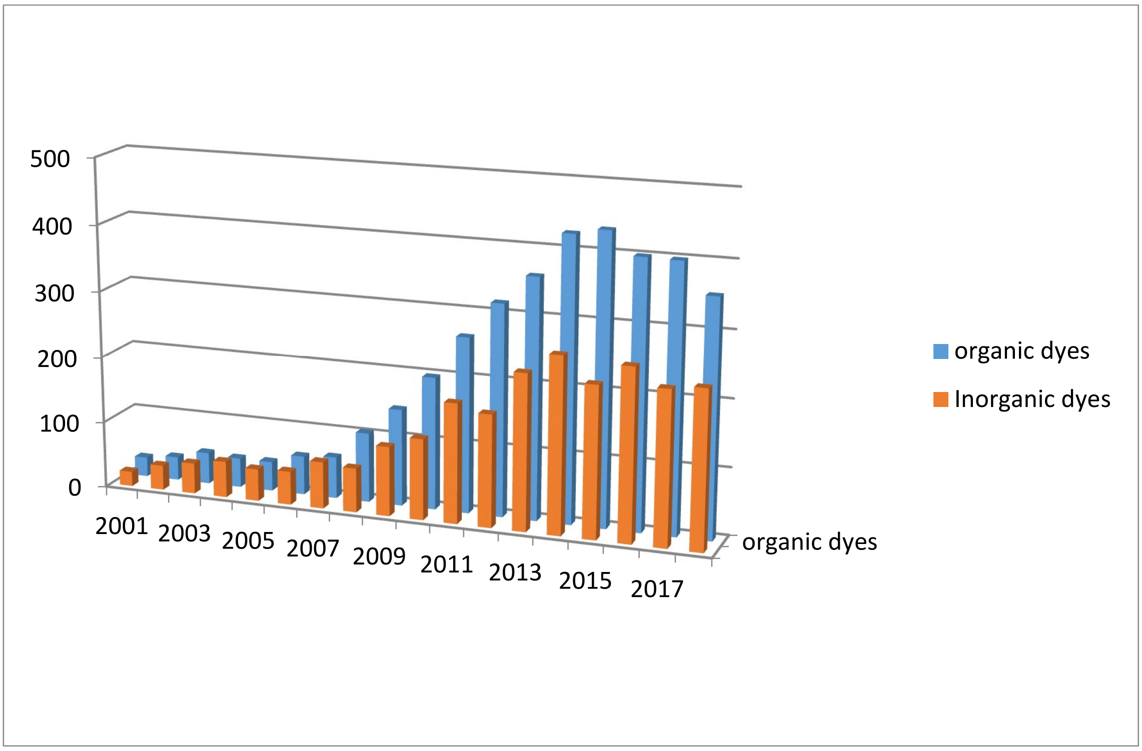


Fig. 8 Literature citation difference between organic and inorganic dyes.

3.4. Exploration of component roles in different technologies using semantic TRIZ.

Regarding the Counter-Electrode, Table 3 highlights the design configuration, materials, and the manufacturing procedure of the counter-electrode component. For instance, row three (Carbon counter electrode) details the architecture of the carbon counter-electrode of nanocrystals bonded with titanium by 3GSolar Ltd. The architecture of row four (Polymer film) devised by Inoue Teruhisa (US-20090242027 A1), from Japan, covers several base materials bonded with a vapor-deposited film of several conductive metal elements. These last examples show that relying only on the number of citations, at least in patents, may lead to inaccurate inferences since patents tend to cover and to cite many materials and substrates to protect intellectual property broadly.

Table 3.

An extraction of counter-electrode materials from patents (patents source PatStat).

Element	Abstract paragraph	Title	Patent	Assignee
1.Platinum counter-electrode	As shown in the Fig., the photosensitized electrode 1 according to the present invention is assembled with a **platinum counter-electrode** 51 to form a slear cell devide filled with an electrolyte 52 inside	InN/InP/TiO2 photosensitized electrode	EP-188759 B1, US-7622397 B2	**Institute of Nuclear Energy Research, Atomic Energy Council**, (Lunghan, China)
2.Nickel counter-electrode	There is no particular limitation to the kind of the counter-electrode 43 as long as the counter-electrode 43 is formed by a conductive substrate. A conductive metal such as titanium, aluminum, and **nickel** can be cited as an example of **counter-electrode** 43. In the counter-electrode 43, in order to promote the redox reaction of the electrolytic solution, a catalyst is provided in a surface contacting the	Dye Sensitized Solar cell	US-20090000661 A1	**Yoshimoto**, Naoki (Hitachinaka Japan)

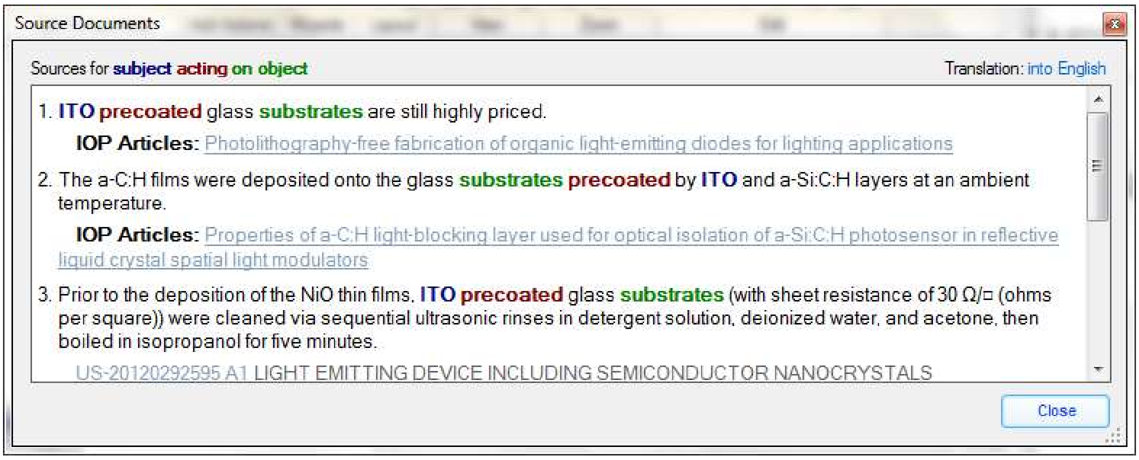
	electrolytic solution. Examples of the catalytic include platinum, graphite, and an organic polymer. The catalyst is provided on the counter-electrode by platinum sputtering, a method of reducing a platinum colloid solution, graphite application, or organic polymer spin coating			
3.Carbon counter-electrode	Each element includes a light facing anode comprising nanocrystalline titania, a **carbon counter-electrode** (cathode) which is a porous, electrically conducting carbon-based structure bonded together using a titania binder, and separating the anode from the cathode is placed an intermediate	Photovoltaic dye cell having an improved counter-electrode	WO-200902977 A2	**3GSOLAR Ltd**. (Israel)
4.Polymer film	Examples of counter-electrodes that can be used include glass or a **polymer film** on which platinum, carbon rhodium, ruthenium or the like are vapor-deposited, or conductive fine particles are applied.	Dye-sensitized Solar Cell	US-20090242027 A1	**Inoue**, Teruhisa (Tokio Japan)
5.Thin Pt layer	The conductive layer and **thin Pt layer** are to be a **counter-electrode** of the solar cell.	Dye-sensitized Solar Cell	US-20090199896 A1	**Oki Semiconductor Co. Ltd.** (Tokio Japan)

The counter-electrode, as every component of the DSSC system, is a ‘subsystem' itself, and therefore, it is constituted of parts or components. The use of semantic analysis and SAO extraction from the documents allowed us to extract the functions of such component. The results collected so far show that most of the materials and techniques of the counter-electrode are also being developed in other industries, such as LCD or TFT screens. Table 4 shows different applications of platinum counter-electrodes and, particularly, a special type of platinum counter-electrode used in the DSSC technology. Such an electrode is obtained by sputtering of a platinum thin layer to use the minimum possible amount of platinum (Cho et al., 2013), yet to have good performance. Even with that particular platinum electrode, it can be seen that different devices, other than DSSCs, take advantage of it for fabricating platinum counter-electrodes.

Table 4. Applications of Pt sputtering counter-electrode.

Pt sputtering electrode Application	**nº of occurrences**
Electrode in fuel cell	59
Counterelectrode in a potentionstat	37
Electrode in light emiting device	23
Counter-electrode in DSSC	21
Counter-electrode in electric-neural interfaces	16
Cathode in thin film sensor	12
Counter-electrode in proteolytic electronic mediator	11
Counter-electrode in transcriptional device	10
Capacitor electrode in flash Eeprom	9
Electrode in PZT capacitor	7

Regarding the photoanode component, Fig. 9 shows that other technologies, such as photosensors or photolithography, also use ITO precoated glass substrates, as in the DSSC counter-electrode. In fact, top ten assignees patenting with ITO precoated glass claim different technologies other than DSSCs, as seen in table 5.



Sources for **subject acting on object**

Translation: into English

1. **ITO precoated** glass **substrates** are still highly priced.

   IOP Articles: Photolithography-free fabrication of organic light-emitting diodes for lighting applications

2. The a-C:H films were deposited onto the glass **substrates precoated** by **ITO** and a-Si:C:H layers at an ambient temperature.

   IOP Articles: Properties of a-C:H light-blocking layer used for optical isolation of a-Si:C:H photosensor in reflective liquid crystal spatial light modulators

3. Prior to the deposition of the NiO thin films, **ITO precoated** glass **substrates** (with sheet resistance of 30 Ω/□ (ohms per square)) were cleaned via sequential ultrasonic rinses in detergent solution, deionized water, and acetone, then boiled in isopropanol for five minutes.

   US-20120292595 A1 LIGHT EMITTING DEVICE INCLUDING SEMICONDUCTOR NANOCRYSTALS

Fig. 9. Systems to which the component ITO precoated glass pertains.

Table 5. Different uses of the component ITO precoated glass

ITO precoated glass substrate Assignees	**Number of patents**	**Most cited uses**
Semiconductor Energy Laboratory	244	Liquid crystal display
Princeton University	201	Organic light emitting devices
Sipix Image	176	Electrophoretic displays
Sumitomo Chemical	168	Light emitting polymers
University of Southern California	121	Organic light emitting devices
University of Michigan	84	Near-infrared emitting organic compounds
Hoffman La Roche	75	VIP Analogs
Dow Global Technologies	72	Quinoline and Triazine compounds for electronic devices

Regarding electrolytes, problem-solution SAO analysis suggests different published solutions to lower the viscosity of RTIL's, paying special attention to the system involved in every SAO. Table 6 offers a list of alternative solutions to lower the viscosity, paired with the technology, and the system to which it is associated. It shows that the problem is not restricted to DSSC's, but also other systems using electrolytes, such as some batteries. As discussed, the components of the DSSC system are not exclusive and their development should also be analyzed in other systems to see which system is driving the progress and which other systems are benefiting from that progress.

Table 6
List of some alternatives to reduce the viscosity of RTIL's

Solution	**System involved**	**Reference**
Dry toluene, **xylene**, **decalin** or the like **containing a nanoscale particulate polytetrafluoroethylene powde**r suspended therein by ultrasonication is added to reduce the viscosity of the RTIL	silicon nanoparticle manufacturing	US 20140227548 A1
Short ether groups reduced the viscosities and melting points of RTILs	lithium ion battery	Organosilicon functionalized quaternary ammonium ionic liquids as electrolytes for lithium-ion batteries; Ionics September 2014, Volume 20, Issue 9, pp 1207-1215
Addition of Acethonitrile exponentially increases diffusion and decreases viscosity of the RTIL/ACN mixtures	electrolytes	Acetonitrile boosts conductivity of imidazolium ionic liquids J Phys Chem B. 2012 Jul 5; 116 [26]:7719-27. Doi: 10.1021/jp3034825. Epub 2012 Jun 21
Reduction of the concentration of LiTFSI in P13TFSI to improve the Li+ conductivity of the electrolyte and because of the decreased viscosity of the electrolyte	lithium-sulfur batteries	Effect of cations in ionic liquids on the electrochemical performance of lithium-sulfur batteries Sci China Chem November [2014] Vol.57 No.11
In the case where R1 to R5 in the general formula [G1] are an alkyl group having 1 to 20 carbon atoms, **carbon atoms having small carbon number** [for example, 1 to 4 carbon atoms] is used because the viscosity of the synthesized room-temperature ionic liquid can be reduced; which is preferable for a power storage device.	Power storage device	US 20140342245 A1

Finally, regarding dye-sensitized component and according to Adner and Kapoor (2016), traditional or existing technologies can extend their life by adopting advances through their environment, extending their life cycle, and hindering the adoption of new technologies. Figure 10 portrays the interchange between the research of perovskite as material in the dye used for DSSC, but later also adopted in traditional silicon solar cells, as thin-film, and poly-junction. It also shows further intense research in silicon solar cells against DSSCs. In 2006 Miyasaka and his group (Green et al., 2014) reported the first use of perovskite as sensitizer and later, in 2008, silicon thin film solar cells started using the same. The adoption of perovskite and the results it brings shows the intense research and the impact in efficiency 22.7 % ([http://www.nrel.gov/ncpv/images/efficiency_chart.jpg visited on 15/6/2019).

Moreover, the decreasing in cost of silicon solar cells may add to the explanation of this large adoption. Innovation systems can be inherently untidy and multiform (Sahal 1983)

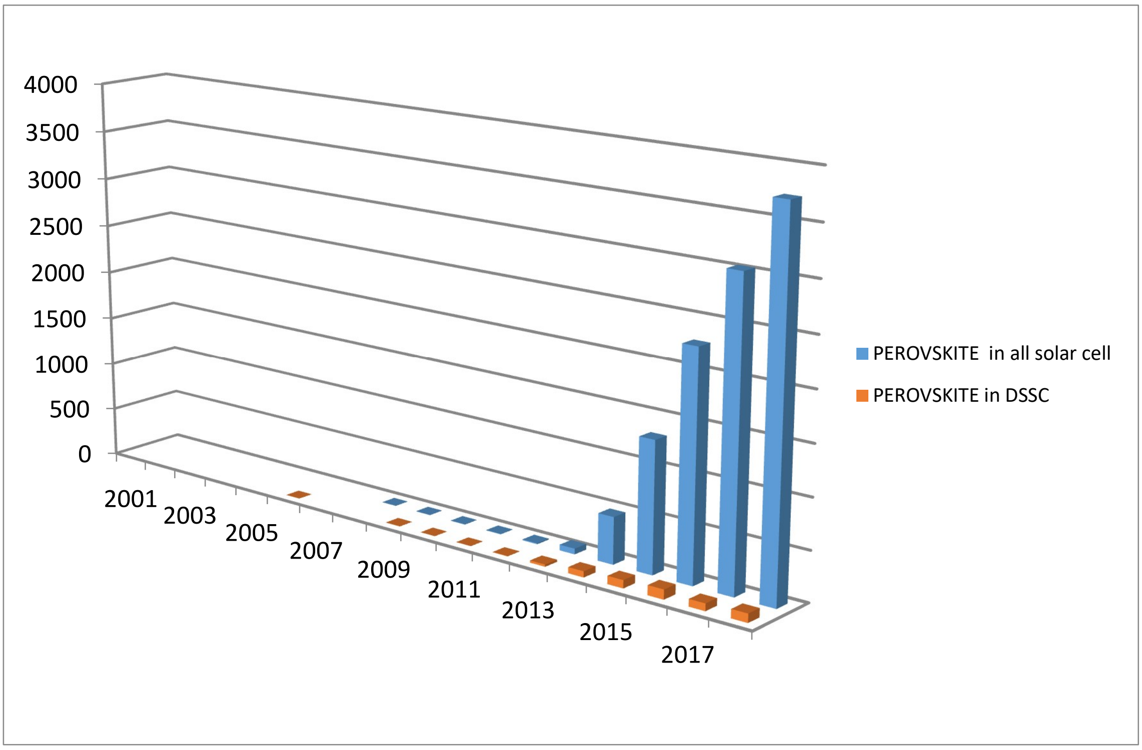


Fig. 10. Different progress of perovskite use in DSSC and in solar cells in general.

As in 2013 appears the use of perovskite as sensitizer (Upadhyaya, 2013), Fig. 10 shows thin film and other solar cells started to use perovskite by that time achieving higher efficiencies (Cho et al., 2017).

7. Discussion

The combination of tech mining and semantic TRIZ has proven to be useful to explore DSSC technology in a systemic way. It shows the cause-effect bond between the trends and the SAO chain function model. The chain SAO model helps to understand the relevance of a given component and the main function, i.e. to produce energy and therefore akin to the efficiency. The semantic links and the mereology helped to identify where other industries or sectors are also using DSSC components, as shown in the case of the perovskite layer. The four-step approach provides a logical framework to treat development of technological activities. It could be used to perform a systemic assessment of a given technology. It combines empirical and expert knowledge in a sequence of quantitative and qualitative analyses about any technology. Combining qualitative and quantitative research findings is the best option to explore complex and heterogeneous projects and systems, often insufficiently understood by policymakers (Holguín-Veras et al., 2017).

Regarding the first research question, TRIZ functional analysis, complemented with a syntactic-semantic TRIZ-based tool, improved the systemic analysis of a given technology by helping to assess its components' configuration and architecture. Furthermore, the systemic point of view helped also to see the whole picture.

The DSSC system shown in Fig. 1 may help to understand some of the current component problems. For instance, in the case of the electrolyte, as noted in Bella and Bongiovanny (2013), there is a clear component conflict in the DSSC system. A good cross-linking by photo-induced polymerization seems to increase its stability and retain its gel-like properties; however, it hinders its conductivity; whereas a less cross-linked electrolyte is less stable but offers higher conductivity. This limiting effect, as well as its advantages and disadvantages or the specificity of its development, could explain the decreasing pace of citation of the electrolyte in general, in comparison with other components, see Fig. 5.

Likewise, the systemic point of view can help to measure structural relationships (functions) among components of a given technology. The systemic analysis also offers a view of the relevance of each component in terms of adding value to a given technology. Figure 1 shows the different components of the DSSC, their functions and the contribution to the main function: producing electrons, i.e. energy. This latter may help to measure and to better understand the importance of research works in the advancement of a given technology.

The hierarchy of DSSC components and the relevance of the dye acting as the ‘tool' of the system, as seen in Fig. 1, have shown different citation trends in the analysis of literature. By identifying the tool of the system, and assessing other components by their contribution to the main function, one should expect different trends and dissimilar trends. The analysis of the functions helps to identify the challenges stated and validated in the analyzed reviews.

As the key tool of the DSSC system, the progress of the sensitized-dye has proven critical in the efficiency of the DSSC (Iqbal et al., 2019). The efficiency records commented in section 3.1. shows that shifts in the dye have had profound effects on the main parameter of the DSSC system – its energy efficiency (Green et al., 2014, Litvin 2011).

With respect to the second research question, the use of semantic TRIZ has helped to explore the interaction of other technologies in the pace of the progression of key components of a given technology. The reason strives in the way a system, ‘S’, and its function, ‘A’, can bring service to different objects, ‘O’ and these relations, S-A-O, can be interpreted in a different order with different outcomes. Prior studies mostly use SAO structures as problem-solution (AO–S) entities to construct a function-oriented database. This entity helps to explain which technical solutions can advance a technological trend or build a richer morphological analysis (e.g. Choi et al., 2012; Wang et al., 2015; Guo et al., 2016). However, the present paper uses SAO structures as ‘system-action--object' (SA-O) rather than problem-solution (AO–S). The present research analyzes the ‘S,' the system, and their components (Figs. 1 to 7) – jointly with functions as interrelations. Importantly, this allows us to associate them with developments in other systems without searching for every technological component “everywhere.” By using the TRIZ functional analysis, the SAO chain, and further the use of a syntactic-semantic analysis, firstly we can identify the existing functions and secondly look for where those functions are used by other systems. The implication is that the components of a given system may be connected to other systems. Its identification may help to explore the trends of such ‘other' systems and compare their interaction in research and development.

Tech mining helps to identify the dominant elements in the literature on a target technology under study. For DSSCs, this supports the emphasis on materials for the dye, the counter-electrode, and electrolyte. The tech mining technique also helped to identify the ‘What' (Vicente-Gomila and Palop, 2013). By exploring the trend in Fig. 2, it seems that platinum and carbon are most used as materials for the counter-electrode. The use of different technologies for the fabrication of the counter-electrode (Li et al., 2011) shows the systemic dimension of said component, see table 4. The ‘tool' in the subsystem ‘counter-electrode' is the layer of Pt in the case of a platinum counter-electrode. According to the relevance of the systems, the tool must be maintained, although the cost of platinum is not practical for large scale manufacturing. Researchers have been modifying the counter-electrode, progressing to the use of fewer quantities of Pt, even to the atomic scale, however maintaining functionality (e.g., He et al., 2014). The same can be said for carbon-based counter-electrodes, although the cost, in this case, is a less relevant issue. Figure 2 shows that despite the lower cost of carbon-based counter-electrodes, researchers seem to prefer platinum counter-electrodes, probably due to its higher conductivity and hence, its efficiency. The combination of trends with the semantic contribution of methods or materials related to the counter-electrodes as seen in Table 3, may improve the view of what is really occurring in the development and evolution of the counter-electrode component in the DSSC system. Table 3 shows different technologies using platinum electrodes produced by sputtering a layer of such material.

As seen in Section 3.4, some components seem to be ‘horizontal' or multipurpose, that is, used in different competing technologies. The case of perovskite used in DSSCs illustrates such a multipurpose character, which has also been rapidly adopted by other thin-film solar cells (as seen in Fig. 10). As Fig. 10 shows, once a new material, perovskite, is used as the ‘tool’ of the DSSC system, because of its impact on its efficiency (e.g., Cho et al., 2018), it is rapidly replicated in thin-film or multifunction solar cells. The parallel trend of DSSC using perovskite, compared to other solar cells also using the same material, shows it is also rapidly adopted by such ‘competing technology’ even with more intense research by the number of articles about thin-film solar cells, from 2013 on. Comparing the pace of citation for DSSCs to that of other solar cells, the DSSC seems to remain lower in time. Recent reviews focus more on the comparison of organic dyes vs. inorganic dyes, as ruthenium or perovskite, shown in Fig. 8. Such technologies may contribute to change the direction of the DSSC R&D, as well as to advance other technologies. It is of great interest to further explore such ‘multipurpose’ materials, and the interaction in other technologies, to see the possible trends or opportunities and if the progress of such materials can also apply to DSSC technology. The syntactic-semantic approach also helps in exploring how other tech systems are related to the analyzed system, and how such connected technologies from the ecosystem may affect the progress of a given technology, as the DSSC technology analyzed in present study. As Fig. 9 and Table 4 show, the identification of cross-application of several components or sub-technologies can also help to understand the links between research areas, related by the technologies to which they pertain.

Table 3 shows the parallel trend of development of material electrodes in the DSSC system and in other technologies. This trending can pose questions such as who is ‘driving' whom? (the chicken or the egg), and therefore who is determining the outcome. In that sense, Yue et al. (2014) mention polypyrrole as a highly used material in other technologies than DSSCs, for instance, in other electrical devices and detectors. Table 3 also shows that the shared problems or functions can help to identify partners within or outside such a technology field, who are heavily engaged in relevant component development. Returning to the relation SA-O, Table 6 shows that some of the limiting problems, as the ion mobility in DSSC electrolyte, appear in other technologies. The solutions implemented in such other technologies may benefit the research in the DSSC.

Finally, the proposed four step approach may complement other scientometric techniques such as IPC analysis, co-word analysis, co-citation analysis, or coupling analysis. It can also contribute to the task of assessing technology evolution and its systemic development progress. This is especially the case in open innovation models that require more information about key technologies, their usage in different industries, and the actors behind them. This paper represents an initial research about the influence of one technology into another to assess implications for potential emergence of each. Further research should be undertaken to systematically take advantage of the benefits derived from this systemic approach.

8. Conclusions

The four step approach is useful to assess emerging technology in a systemic way. The combination of tech mining and semantic TRIZ enriches the analysis of technology evolution through mining of ST&I information resources. The approach offers an empirically based procedure, buttressed by expert review, for the analysis of technology and science progress which helps: 1) to better understand multidimensional aspects of technological development, 2) to understand why some components in a given technology may progress faster than others, and 3) to understand the possible interaction of other technologies in the pace of progression of a component of the studied technology.

The present findings suggest that knowing the systemic functional organization of the system can help understand where to concentrate on one's future R&D efforts. This point should be further explored across technologies. A systemic view could prove worthwhile to provide key insights for characterizing R&D activity vis-a-vis evolution potential in multiple technologies.

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