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Review

Comparing Patent and Scientific Literature in Airborne Wind Energy

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Abstract: Airborne Wind Energy (AWE) is a renewable energy technology that uses wind power devices rather than traditional wind turbines that take advantage of the kinetic wind energy, and remain in the air due to aerodynamic forces. This article aims to compare the scientific literature with the patents on wind power with tethered airfoils, to obtain better insights into the literature of this area of knowledge. The method used in this study was a comparative bibliometric analysis, using the Web of Science and Derwent Innovations Index databases, and the Network Analysis Interface for Literature Review software and VosViewer. It was possible to verify the main authors, research centers and companies, countries and journals that publish on the subject; the most cited documents; the technological classes; and the networks of collaborations of this work. It was also possible to identify that researches on wind energy with tethered airfoils began their studies in the late 1970s with the first patent apparently dated from 1975 by the inventors Dai and Dai. The first scientific publication was in 1979 by authors Fletcher and Roberts, followed by Loyd in 1980. United States is the country that presented the highest number of patents and scientific papers. Both scientific papers and patents set up networks of collaboration; that is, important authors are interacting with others to establish cooperative partnerships.

Keywords: airborne wind energy; patents; literature review

1. Introduction

In recent years, important themes related to social well-being have been discussed, and among these themes the world energy matrix has received special attention. Energy is fundamental for the social and economic development of a country, being fundamental for the provision of services such as water supply, food, health, education, employment and communication. Today, most of the energy consumed worldwide comes from fossil fuels (e.g., coal, oil and natural gas), which are not in conformity with new environmental legislation aimed at improving the quality of life of living things and the natural balance of the environment [1].

To address these problems, many countries are adopting energy policies focusing on the increasing of renewable technology deployment, such as hydroelectric and small hydropower plants, wind energy, solar energy, marine energy, biomass, and so on. In this study, the focus is on a new renewable energy technology: Airborne Wind Energy (AWE). This innovative technology for renewable energy exploration uses aerial devices rather than traditional wind turbines to make use of wind kinetic energy and it can remain in the air through aerodynamic forces [2–4]. Unlike wind turbines with towers, airborne wind power systems operate in flight and they are connected to a foundation by a cable, either to transmit the energy generated at the airfoil or to transmit mechanical energy to the generator on the ground. The airfoils may be rigid or flexible wings and the energy is harvested by exploiting the aerodynamic lift and drag forces produced on the airfoil by the wind [3]. In some cases, tethered balloons can also be used [3].

The advantages of this innovative technology, when compared to other technologies established such as wind turbines, are lower costs of construction, installation and transport, higher probability of reaching stronger and consistent winds and higher speeds at high altitudes. AWE can reach 600 m above the ground, and therefore can exploit a greater energy potential [5]. Wind technology with towers cannot take advantage of this potential due to structural and economic factors that limit the use of wind towers to a maximum height of approximately 125 m [6].

The different approaches used in AWE technology can be seen in Figure 1. These examples are different because of the type of airfoil, how it holds suspended in the air, and whether the electric generation occurs on board or on the ground. Many technologies based on these concepts are being developed around the world.

Approaches dealing with aerodynamic elevation can be found in References [7–13]. They make use of airplane wings or kites to generate energy and in the form of aerostatic elevation, which utilizes structures lighter than air (such as balloons) that may have generators on board [14] or positioned on the ground [9,11,15]. In this case, the electric energy can be generated by the airfoil and transmitted to the ground by cable. Electric energy can also be generated on the ground by a cable that transmits the mechanical energy generated by the airfoil. Technologies using balloon-type airfoils generate energy in flight and transmit it to the ground through a cable [15].

Figure 1. From left to right, the prototypes of Airborne Wind Energy generators: a generator positioned on the ground with TU Delft's flexible airfoil [9], a generator positioned on the ground generator with rigid airfoil from Ampyx Power [11], a GoogleX system with onboard generators [12], balloon with onboard turbine from Altaeros Energies [15], and generator positioned on the floor with flexible airfoil from UFSCkite [16].

The potential of AWE technology with tethered airfoils has been investigated for more than three decades. Several authors refer to the pioneering work of Loyd [2] in 1980 as the precursor of studies of AWE technology. Loyd showed that high aerodynamic forces can be obtained when airfoils are operated in high-speed maneuvers. Loyd was the first to investigate and calculate the power generation potential with a high-speed tethered airfoil. He described two ways of generating electric energy by AWE technology: (i) lift mode with generators on the ground; and (ii) drag mode with onboard generators. These ways can be found in Crosswind kite power (for large-scale wind power production).

Patent analysis has demonstrated that wind, geothermal, and hydro technologies represent only 8% of the total amount of granted (patents) despite the fact that they are widely recognized as effective and sustainable technologies to be used in the next future [17]. Patent data have greatly attracted both researchers and practitioners. Patent data can be used to take into account the results of innovation activities [17,18]. Patent data have emerged as valuable sources of information for studying innovative dynamics. Ardito et al. [19] argue that the question of how breakthrough inventions come to exist is not new to the literature.

According to Albino et al. [17], patents do not portray the whole innovative portfolio. Additionally, some innovations are not patentable and patents do not always represent the most suitable mechanism to protect innovations. The value of patents can vary across countries and the characteristics of appropriation regimes may affect the propensity to patent. Finally, not all patented inventions are actually implemented in market applications [20]. For example, Ardito et al. [19] attempt to fill in the literature gap on the types of invention that can become breakthroughs, by providing more insights into the ongoing debate about the role of nascent versus existing technologies. In another study, after analyzing 88,748 patents in the "Alternative energy production" and "Energy conservation" technological classes, Ardito [21] finds that when an organization's inventive team, devoted to develop a new technology, is large or geographically dispersed in diverse countries, one can derive greater benefits from a wider search breadth.

A mentioned earlier, this article aims to compare the scientific literature with patents on wind energy with the use of tethered airfoils in order to obtain better insights into the state of the art of this technology.

This article consists of four main sections, including this introduction. Section 2 presents the theoretical framework informing the study. Section 3 describes the materials and methods used to analyze the two basic sources of information here proposed: scientific literature and the patents selected for the analysis. Finally, Section 4 provides the conclusions of the study.

2. Theoretical Framework

Airborne Wind Energy (AWE) or High Altitude Wind Energy (HAWE) is a branch of research in the relatively new wind energy field that uses aerial devices instead of conventional wind turbines to extract a portion of the wind's kinetic energy, and convert this energy to electricity [22,23]. These devices called tethered airfoils, in some cases use wings like that of a paraglider or kitesurf or like a balloon or airplane wings. Several structures with tethered airfoils have been studied for harnessing the energy of the winds at high altitudes. They differ, for example, in relation to the type of wing, which can be rigid or flexible; as to the location of the electric generator, which can be on the ground or suspended in the air; in terms of the aerodynamic power being exploited, drag or lift; and finally, as to how to control the flight of the airfoil, which depends on the number of cables and the position of the actuators and sensors. This technology has begun to be intensively studied in recent years, although commercial products are not currently available, significant research and investments are currently being made.

Aloys Van Gries [24] launched a 398-page book in 1921 and its main theme was "aircraft". This book is available in German by Springer Publishing Company with the title "Flugzeugstatik" [Aircraft Statistics]. The book might give some clues to Aloys van Gries' mind that later brought about the filing of his patent on the AWES scheme. In this book, there are robust analyses of biplane aircraft structures; especially for those interested in the field of biplane aircraft. In 1935, Aloys van Gries filed the patent on airborne wind energy, about 15 years following the publication of his major textbook on aircraft statics.

Therefore, the first patent on Airborne Wind Energy can be attributed to Van Gries and it dates back to 1938 (GB489139) [24]. This patent is related to improvements in or relating to wind-driven power apparatuses. According to Van Gries [24], the energy generated by the wind wheel may also be led or transmitted mechanically straight to the ground by means of the guy-rope. In this invention, he provided a wind-driven power apparatus for utilizing high winds, wind-driven machines that are held by captive kites, characterized using a system of interconnected kites. This way the lifting power can be increased to a practically unlimited extent as any desired number of kites can be coupled together. Each kite must carry only that part of the guy-rope that connects it to next lower kite. The result is that the strength of the guy-rope, particularly towards the upper end, can be small whilst, with a single kite, because this large dead weight, it must be as strong as possible at the upper end.

It further follows that each kite of the system, as its lifting power exceeds the weight of the pertaining guy-rope, increases the total lifting power. Therefore, it is possible, by means of the wind-driven machine, to bring large weights to great heights and thus utilize the stronger and more uniform high winds. Then, a guy-rope is utilized for the power transmission or, if the change of wind energy into electricity is to be effected on the kite system itself, it is formed as a cable for conducting the electric current being produced [24].

In 1939, Hermann Honnef described the design for an arrangement of wind turbines atop a tower approximately 300 m in height, designed to take advantage of the faster winds found at high altitudes [25,26]. Interest in high altitude wind energy increased in the 1970s and 1980s as a response to the oil crises, with small groups and individual researchers first publishing their ideas and concepts. For example, Hermann Oberth in 1977 presented a design for a "kite power plant": a wind turbine lifted up to 12,000 m in altitude by a balloon, and secured by a long tether to the ground [27,28]. The Kite Power Station is a wind-driven power station at high altitudes.

Kambouris [29] explains that as fossil fuel prices lowered from the crisis peaks, interest in these ideas waned over the 1980s and 1990s, with little published during this time. Since the mid 2000s, there has been a resurgence of interest and AWE has begun to emerge as a recognized field of research, with its own association, conferences, and a considerable body of academic publications.

An overview of the state of the art on AWE technology can be found in [23,30]. Figure 2 presents a world map with the 55 research institutions around the world actively engaged in Research and Development (R & D) in this area.

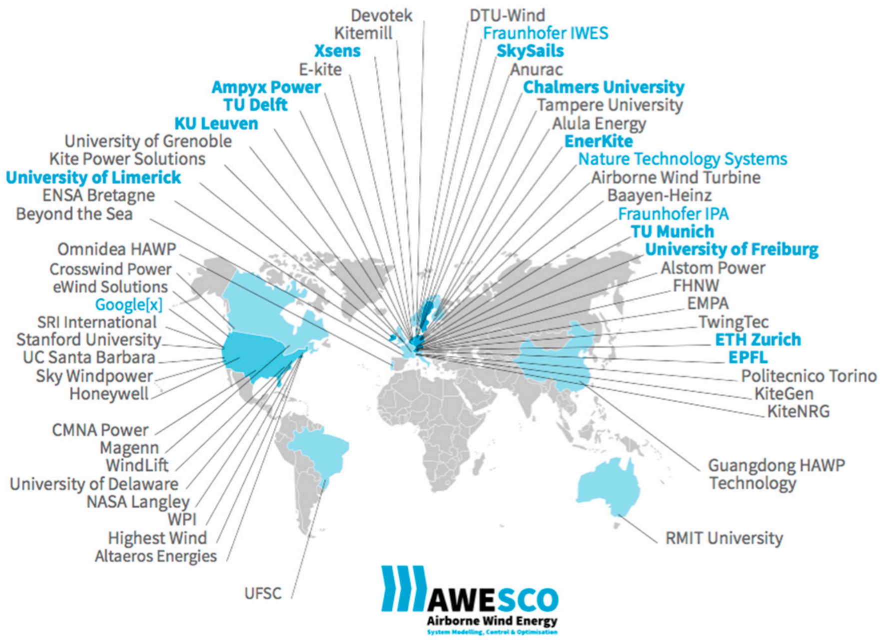

Figure 2. Institutions involved in R & D and using AWE technology in 2015 [30].

These groups aim to harness available wind energy at higher altitudes in relation to current wind technology. In this sense, this study can justify its method of comparing the scientific literature with the existing intellectual properties (i.e., patents) on the subject.

3. Materials and Methods

This research has a more theoretical nature in relation to the topic addressed. As for its technical procedures, it is framed as a bibliographic study, since it will deal with data and verifications based on work already done about the researched subject. From the point of view of the objectives, it is classified as exploratory and descriptive, as it will seek specific information and characteristics of what is being studied [31].

Literature review means for the researcher the first step in the quest to develop a work and build knowledge in each context. It also allows an introductory view on the development of a research project and takes back the accumulated scientific knowledge about the subject [32]. It allows the researcher to become even more familiar with the researched topic, enabling him to create new constructs and definitions.

In this context, a bibliometric analysis was carried out, which is a technique for mapping the main authors, journals and keywords on a given topic. This technique uses tools that rely on a scientifically-recognized methodological theoretical basis, which enable the use of statistical and mathematical methods to map information from bibliographic records of documents stored in databases [33]. This method was divided into three stages, which are presented in Figure 3 and described in the following.

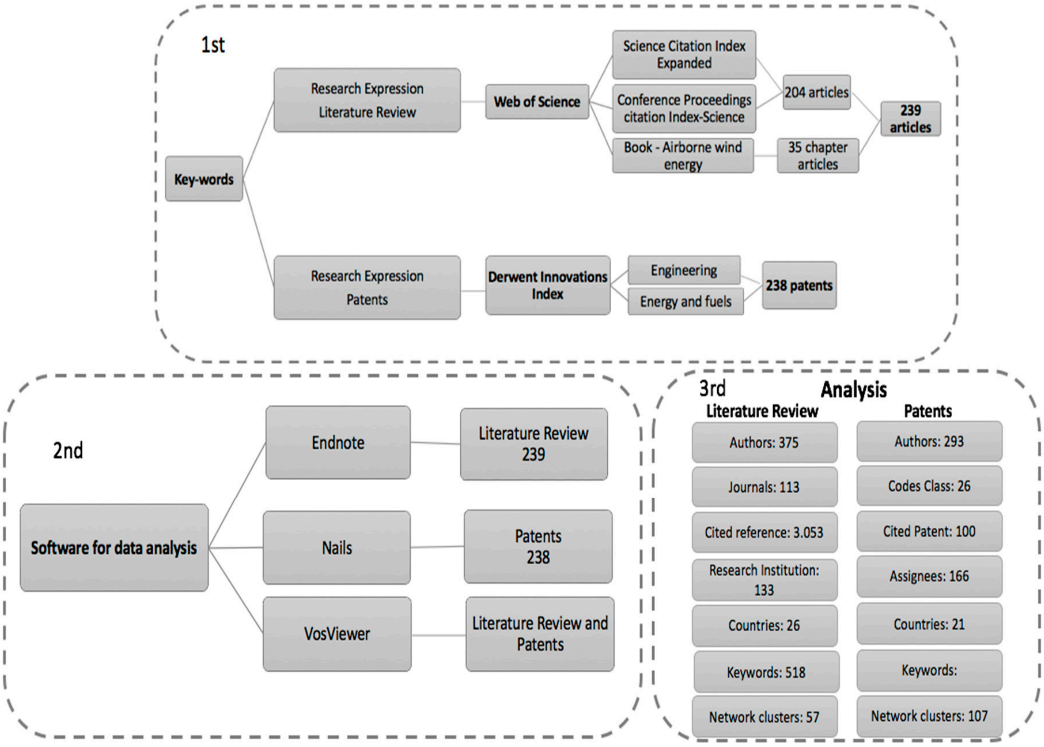

Figure 3. Methodological procedures of the research.

The first step was to define the keywords and the database to be explored. The database to be consulted was chosen from the Capes (Coordination for the Improvement of Higher Education Personnel) journal portal, Web of Science, because it is multidisciplinary and indexes only the most cited journals in their respective areas. It is also an index of citations, informing, for each article, the documents cited in it and the documents that cited it. Today it has more than 9000 indexed journals. In this research, documents indexed by the Science Citation Index Extended (SCI-Expanded) and Conference Proceedings Citation Index-Science (CPCIS) were used. CAPES Periodicals Portal does not provide access to the Web of Science's Book Citation Index-Science subbase, so the authors chose to manually include the book "Airborne Wind Energy" (the Springer textbook "Airborne Wind Energy" from 2013, with 35 peer-reviewed book chapters that cover the entire field and has more than 60,000 downloads).

The Patent database, chosen from the Derwent Innovations Index of the ISI Web of Knowledge, is a powerful patent search tool that combines Derwent World Patents Index®, Patents Citation Index™

and Chemistry Resource. Derwent Innovations Index is updated weekly. This Patent database has more than 16 million practical inventions from 1963 to the present day. Patent information is collected from 41 patent authorities around the world and is classified into three categories or sections: Chemical, Engineering and Electrical and Electronic.

The keywords used for this research were validated by a specialist in the area, Table 1.

Table 1. Keywords.

Keywords	Expression
keywords for literature review	TS=("Airborne Wind Energy") OR TS=("Airborne Wind Power") OR TS=("High Altitude Wind Energy") OR TS=("High Altitude Wind Power") OR TS=("Kite wind generator$") OR TS=("kite wind energy") OR TS=("Crosswind kite$") OR TS=("Airborne Wind Turbine$") OR TS=("Flying Electric Generator$") OR TS=("Kite power") OR TS=("Kite energy") OR TS=("Pumping kite$") OR TS=("Lighter-Than-Air Wind Energy System$") OR TS=("Kite model$") OR TS=("tethered undersea kite$") OR TS=("Kite-Based Wind Energy") OR TS=("kite wind power") OR TS=("Kite-Powered System$") OR TS=("Kite towed ship") OR TS=("crosswind towing") OR SO=("Airborne Wind Energy") OR TS=(Parawing AND energy) OR (TS=(Kite) AND TS=("ship propulsion")) OR (TS=("Wind Power") AND TS=("flying kite$")) OR (TS=("kite") AND TS=("tracking control")) OR (TS=("kite") AND TS=("flight control")) OR (TS=("Kite generator") NOT DO=("10.1007/s00145-015-9206-4")) OR (TS=("Towing kite$" AND "wind energy")) OR (TS=("Kite system$") AND TS=("Wind energy")) OR (TS=("Kite system$") AND TS=("Power Generating")) OR (TS=("Power Kite$") AND TS=("Wind Energy")) OR (TS=("Tethered Airfoil$") AND TS=("Wind Energy")) OR (TS=("kite system") AND TS=(wind) NOT DO=(10.1007/BF00123534)) OR (TS=(kite) AND AU=("Creighton, Robert")) OR (TS=(Laddermill) AND TS=(kite)) OR DO=("10.2514/3.48003") OR DO=("10.1016/0167-6105(85)90015-7") OR DO=("10.1016/j.apenergy.2013.07.026") OR DO=("10.2514/1.31604") OR DO=("10.1002/rnc.1210")
keywords of the search for patents	TS=("Airborne Wind Energy") OR TS=("Airborne Wind Power") OR TS=("High Altitude Wind Energy") OR TS=("High Altitude Wind Power") OR TS=("Kite wind generator$") OR TS=("kite wind energy") OR TS=("Crosswind kite$") OR TS=("Airborne Wind Turbine$") OR TS=("Flying Electric Generator$") OR TS=("Kite power") OR TS=("Kite energy") OR TS=("Pumping kite$") OR TS=("Lighter-Than-Air Wind Energy System$") OR TS=("Kite model$") OR TS=("tethered undersea kite$") OR TS=("Kite-Based Wind Energy") OR TS=("kite wind power") OR TS=("Kite-Powered System$") OR TS=("Kite towed ship") OR TS=("crosswind towing") OR TS=("Parawing AND energy") TS=("Airborne Wind Energy") OR TS=("Airborne Wind Power") OR TS=("High Altitude Wind Energy") OR TS=("High Altitude Wind Power") OR TS=("Kite wind generator$") OR TS=("kite wind energy") OR TS=("Crosswind kite$") OR TS=("Airborne Wind Turbine$") OR TS=("Flying Electric Generator$") OR TS=("Kite power") OR TS=("Kite energy") OR TS=("Pumping kite$") OR TS=("Lighter-Than-Air Wind Energy System$") OR TS=("Kite model$") OR TS=("tethered undersea kite$") OR TS=("Kite-Based Wind Energy") OR TS=("kite wind power") OR TS=("Kite-Powered System$") OR TS=("Kite towed ship") OR TS=("crosswind towing") OR TS=("Parawing AND energy") OR TS=("Laddermill") OR TS=("flying kite$")

The research expressions used in the advanced search of the Web of Science are spelled out as follows: TS: topic; DO: DOI; SO: publication name; and the use of Boolians: AND, OR, NOT for search magnification. The search did not set a period, however, the access to Capes Periodicals Portal covers the time span between 1963 and 2017.

The second step was the choice of software for data analysis. The researchers opted for the Network Analysis Interface for Literature Review (NAILS) software, because it is a literature review tool that utilizes several customized statistical and network analysis functions to provide the user an overview of the Literature [34]. It has a unique interface with the Web of Science database, both in the analysis of the data of the scientific literature and of patents, comparing them. NAILS were used in this research for the quantification of inventors, classification of IPC codes, depositors, countries, patents cited and keywords.

As for the network analysis, VosViewer is a software application used to build bibliometric networks based on data downloaded from bibliographic databases such as Web of Science and Scopus. The software enables the user to choose between the use of the total and the fractional counting method [35]. VosViewer was used in this study to generate the collaboration network of authors (literature review) and inventors (patents).

The third step was to analyze the results obtained by the software of the scientific literature and the results of the patents.

4. Results and Discussion

The survey was conducted in April 2017. We found a total of 239 scientific literature papers, which were extracted from Web of Science Core Collection databases and 238 patent documents extracted from the Derwent Innovations Index published between 1980 and 2017.

Table 2 presents the results of the distribution by document type. As shown in Table 1, the most representative types of documents were patents, proceedings papers, articles and book chapters, accounting for more than 99% of the total publication. The 239 documents were written by 375 authors and co-authors. Together, they used 2532 references and 518 keywords. These documents were produced by 133 research institutions from 26 countries and published in 113 journals. It was observed that English is the dominant language with 235 records (98%), followed by Chinese with two and German with one record. As to the 238 patent documents found, they were deposited by 293 authors and co-authors, and belong to 26 classes, 21 countries and 166 assignees.

Table 2. Document type.

Document Type	Count	(%)	Cumulative (%)
Patents	238	49.9	49.9
Proceedings paper	118	24.7	74.6
Article	81	17.0	91.6
Book Chapter	35	7.3	99.0
Article; Proceedings paper	4	0.8	99.8
Review	1	0.2	100.0
Total	477	100.0	

When comparing the trends between the scientific literature and the patents, it can be observed that the scientific literature represents in this research 50% of the publications and the patent applications account for 50%. Figure 4 shows the distribution of publications of scientific articles and patents related to the subject within the period 1975–2017. It can be observed that the scientific literature with airborne wind energy beginning in the late 1970s with the research Electricity Generation From Jet-Stream Winds by Fletcher and Roberts [36], and Crosswind kite power by Loyd [2] in 1980. The first patent located in the search of this particular area had been filed by Dai and Dai [37] in 1975 with the title "High-altitude wind energy combined solar generation device, has balloon connected with pulling rope that is connected with kite generating device, where pulling rope is fixedly connected with fixed block". This patent was included in class Q54 and X15. Both publications came out in the mid and late 1970s; and it is noteworthy that first a patent was obtained on the subject and four years later a scientific publication emerged.

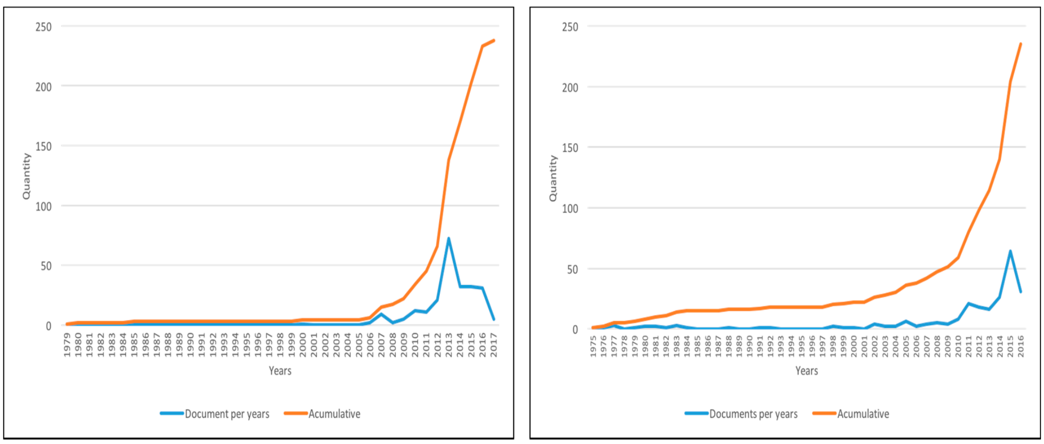

Figure 4. Scientific articles published per year (left); Applications for patents per year (right).

The 239 papers in the literature were published by 375 authors from 133 research institutions in 26 countries (Figure 5). The most prominent authors were Fagiano (32); Diehl (21); Adhikari, Olinger and Panda (11); Hably, Milanese, Vermillion and Ockels (10); and Schmehl (9). Fagiano, Milanese, Ockels and Schmehl are also the ones who figure on the list of most cited authors.

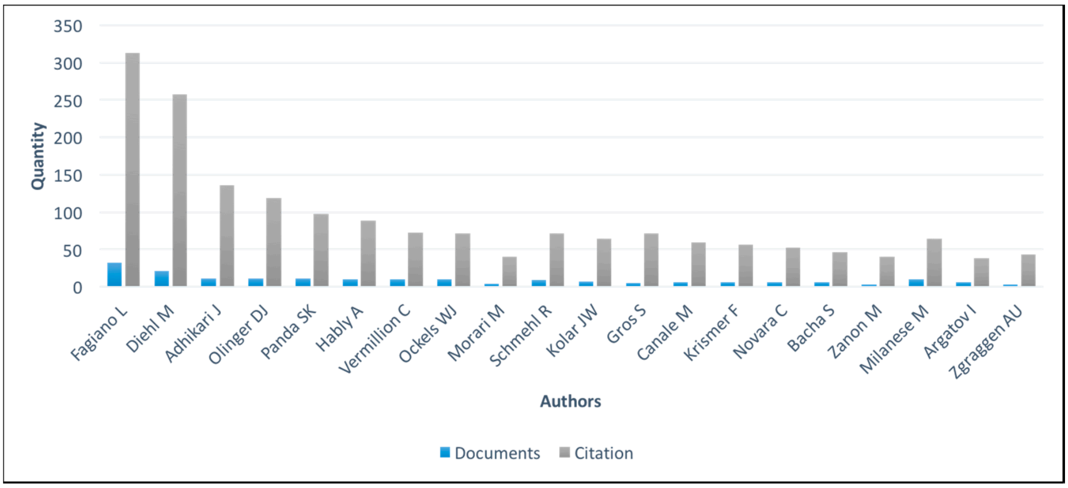

Figure 5. Authors with the largest number of documents versus authors with the largest number of citations.

Fagiano, Lorenzo is a professor and researcher at Politecnico di Milano, Department of Control and Computing Engineering (DAUIN). He works in Systems and Control include robust constrained control, Model Predictive Control (MPC), efficient MPC implementations and Set Membership theory for control purposes, with applications to high-altitude wind energy generation. In this search, he was considered the most active researcher with 32 publications. He is also inventor of two international patents, registered in nine countries, in nine different classes. The numbers of the Fagiano, L., Gerlero, I. and Milanese, M. patents are "WO2011121557-A2; WO2011121557-A3; CA2794344-A1; EP2553262-A2; US2013078097-A1; IT1399971-B; JP2013527893-W; CN103038501-A; IN201208254-P4; RU2012146377-A; EP2553262-B1; JP5841124-B2; RU2576396-C2; US9366225-B2", productive assignees were KITENERGY SRL and MODELWAY SRL.

Milanese, Mario has carried out research in the areas of control systems engineering, automotive and aeronautical engineering, mechatronics, renewable energy and space power, wind power and power systems and automation and control, and has 10 published articles with 120 citations. He is a professor and researcher at Politecnico di Torino, Turin, Italy. He maintains collaboration with the researchers Fagiano, L., Razza, V., Bonansone, M., Canale, M., Piga, D., and Novara, C.

Diehl, Moritz studied physics and mathematics at Heidelberg and Cambridge University from 1993 to 1999 and obtained a Ph.D. degree from Heidelberg University in 2001 at the Interdisciplinary Center for Scientific Computing. From 2006 to 2013, he was a professor with the Department of Electrical Engineering, KU Leuven University Belgium, and served as the Principal Investigator of KU Leuven's Optimization in Engineering Center OPTEC. Since 2013, he has been a professor at University of Freiburg, Germany, where he heads the Systems Control and Optimization Laboratory, in the Department of Microsystems Engineering (IMTEK). His research focuses on optimization and control, spanning from numerical method development to applications in different branches of engineering, with a view to embedded and renewable energy systems. He maintains collaboration with Gillis, J; Goos, J; Geebelen, K; Swevers, J., Zanon, M., Ahmad, H; Vukov, M., Andersson, J., Horn, G., Meyers, J., Stuyts, J., Vandermeulen, W., Driesen, J., and Wagner, A. These authors are researchers or have been researchers at IMTEK. As to Frison, G., Jorgensen, J.B., they are collaborating researchers at DTU Compute—Department of Applied Mathematics and Computer Science Technical University of Denmark—and Horn, G is a collaborator of Systems Engineer at Kitty Hawk in Mountain View, California, USA.

Ockels, Wubbo Johannes was a Dutch physicist and an astronaut of the European Space Agency (ESA). In 1985 he participated in a flight on a space shuttle (STS-61-A), making him the first Dutch citizen in space. After his astronaut career, Ockels was professor of Aerospace for Sustainable Engineering and Technology at the Delft University of Technology. He obtained his MSc degree in physics and mathematics in 1973 and subsequently a PhD degree in the same subjects in 1978 from the University of Groningen. His thesis was based on experimental work at the Nuclear-physics Accelerator Institute (KVI) in Groningen.

Schmehl, Roland is Associate Professor at Delft University of Technology at the Aerospace Engineering faculty. He has an extensive background in Computational Fluid Dynamics in the fields of low emission combustion, liquid propellant space propulsion, airborne wind energy, kite power generation and airbag deployment. He is active researcher in the exploring of the potential of kite power generation and propulsion.

The 238 patent documents were applied by 293 inventors; Vander Lind (38), Hachtmann (16), Goldstein (13) and Jensen (10) stand out, as shown in Figure 6.

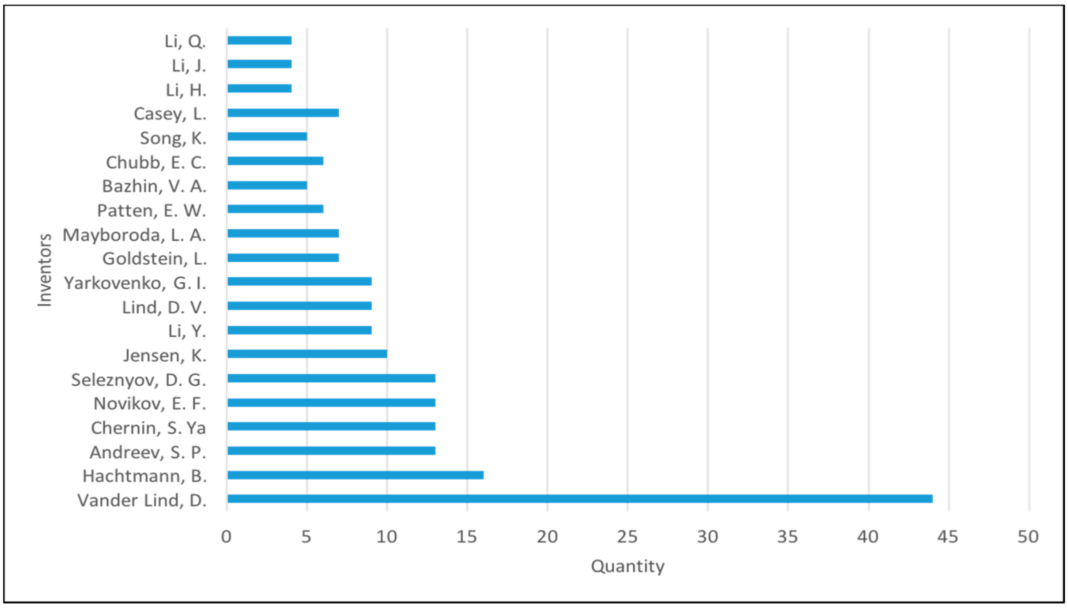

Figure 6. Inventors with the largest number of patents.

Damon Vander Lind has B.S., physics, computer science/electrical engineering (2003–2008) from the Massachusetts Institute of Technology. Vander Lind was Chief Engineer at Makani Power, Inc. Makani Power develops wind energy extraction technology. The company was founded by Saul Griffith in 2006 and is headquartered in Mountain View, California, USA. He now works for Kitty Hawk. He was considered in this research the most active inventor with 38 patent documents.

Hachtmann, Brian holds a Master of Science degree in Mechanical Engineering (2006–2008) from Stanford University. He is Ground Station Team Leader, Mechanical Engineer at Google, in Mountain View, California, USA, who is responsible for 16 patents.

No bibliography was found about the inventors Sergey Pavlovich Andreev, Sergey Yakovlevich Chernin and Evgeni Fedorovich Novikov.

In relation to the sources of publication, Figure 7 presents the five prominent journals on AWE technology: Airborne Wind Energy (book), Renewable Energy, 2016 American Control Conference (ACC), IEEE Transactions on Control Systems Technology, and 2012 American Control Conference (ACC).

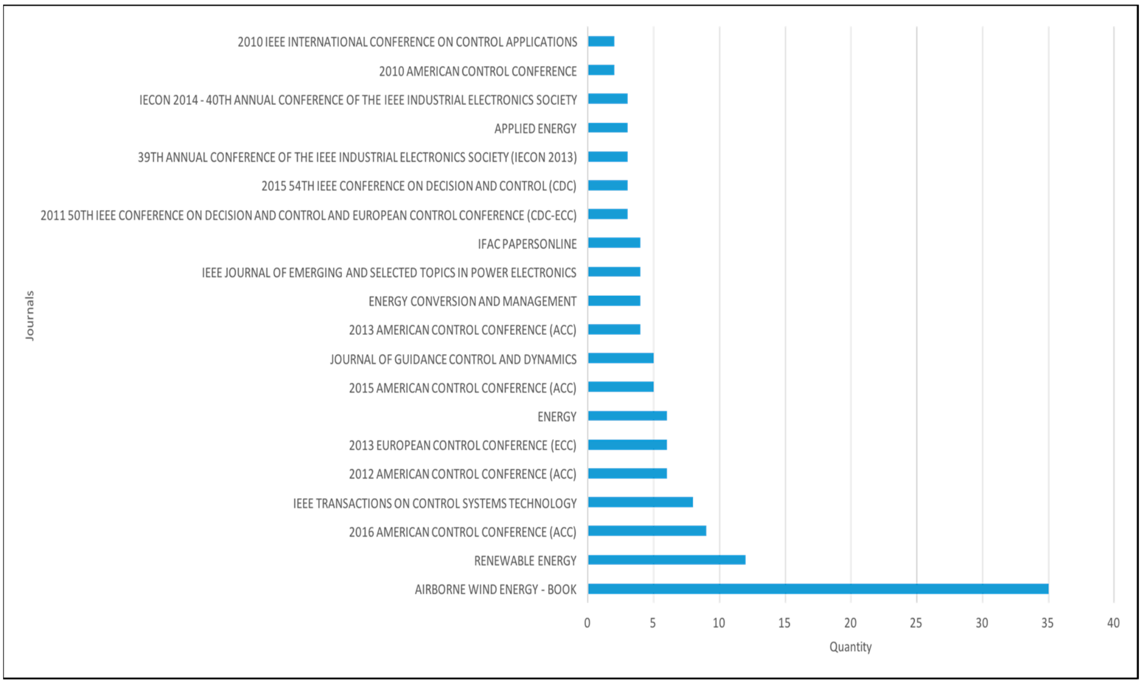

Figure 7. Top journals or conference proceedings and books on airborne wind energy.

The book Airborne Wind Energy provides an overview of the AWE research field. It is the first book that provides a consistent compilation of fundamental theories, current research and development activities, and economic and regulatory issues. The book is divided into 35 chapters [3,7–12,15,38–64] that demonstrate the relevance of AWE and the important role that this technology can play in the transition to a renewable energy economy.

The Journal Renewable Energy is a multidisciplinary journal in renewable energy engineering and research that seeks to promote and disseminate knowledge on topics related to renewable energy technologies.

The American Control Conference (ACC) is the annual conference of the American Automatic Control Council (AACC), the U.S. national member organization of the International Federation for Automatic Control. AACC is an association of the control-related groups of eight member societies: AIAA (American Institute of Aeronautics and Astronautics), AIChE (American Institute of Chemical Engineers), ASCE (American Society of Civil Engineers), ASME (American Society of Mechanical Engineers), IEEE, ISA (International Society of Automation), SCS (Society for Computer Simulation), and SIAM (Society for Industrial and Applied Mathematics). The ACC is internationally recognized as a scientific and engineering conference dedicated to advancing control theory and practice, bringing together an international community of researchers and practitioners to discuss the latest discoveries in automatic control. It covers systems theory and practice, including topics such as biological systems, vehicle dynamics and control, cooperative control, control of communication networks, control of distributed parameter systems, uncertain systems, game theory, among others. The 2012 American Control Conference (ACC) was held in Montréal, Quebec, Canada, being the first ACC outside the United States. The 2016 American Control Conference (ACC) was held in Boston, MA, USA.

The IEEE Transactions on Control Systems Technology publishes papers on technological advances in control engineering. It aims to fill in research gaps between theory and practice in control engineering systems. The materials published by IEEE Transactions on Control Systems Technology reveal new knowledge, exploratory developments or practical applications in all aspects of the technology that need to implement control systems, from analysis and design to simulation and hardware.

As to the analyses of technology classes, they were in accordance with CPI (Chemical Patents Index)—classification used by the Derwent Innovations Index. The patents found in this study belong to classes X15, Q54, W06, Q25, and P36. The X15 and Q54 classes belong to the Green Technology area, in the Green power sources and energy generation theme, the Hydroelectric power inquiry, along with dams, generators, mini/micro plants, pumped storage, and turbines/water wheels. The W06, Q24 and Q25 classes are in the Green Technology area, in the Green Transportation, in the aircraft, pedal power and boat inquiry, along with electric propulsion and wind power.

Patents were also analyzed according to the International Patent Classification (IPC). IPC is the international classification system, created by the Strasbourg Agreement (1971), whose technological areas are divided into classes A and H. Within each class, there are subclasses, main groups and subgroups, by means of a hierarchical system. The classes deposited by the 238 research patents belong to classes A63, B, C10, D07, E, F, G and H, as shown in Figure 8.

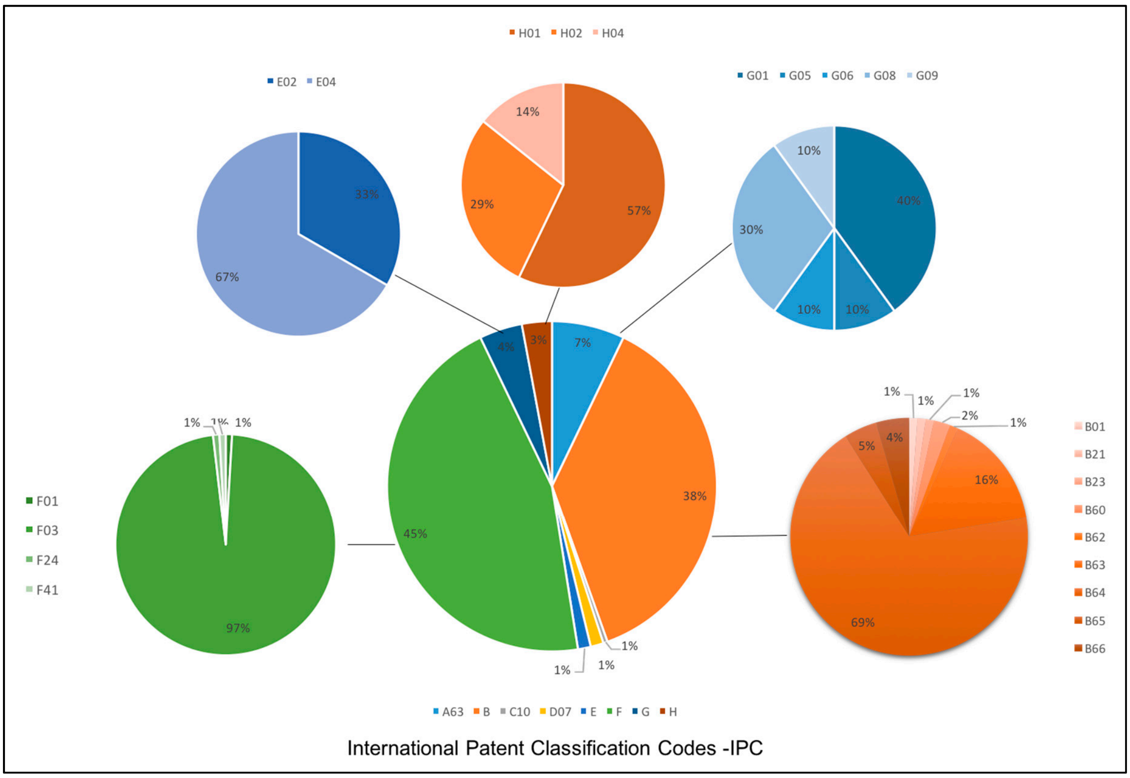

Figure 8. Top International Patent Classification Codes-IPC.

Figure 8 shows that 45% of patents belong to class F and focus on mechanical engineering, lighting, heating, and weapons (subclasses F01, F03, F24 and F41, respectively). Thirty-six percent of patents belong to class B patents for processing and transport operations in subclasses B01, B21, B23, B60, B62, B63, B64, B65 and B66.

The institutions providing the publications in both the scientific literature and the patents are displayed in Figures 9 and 10. Figure 9 shows that the five most representative institutions are Politecnico Torino, Katlolieke University Leuven, Delft University of Technology, National University Singapore, and Worcester Polytech Inst.

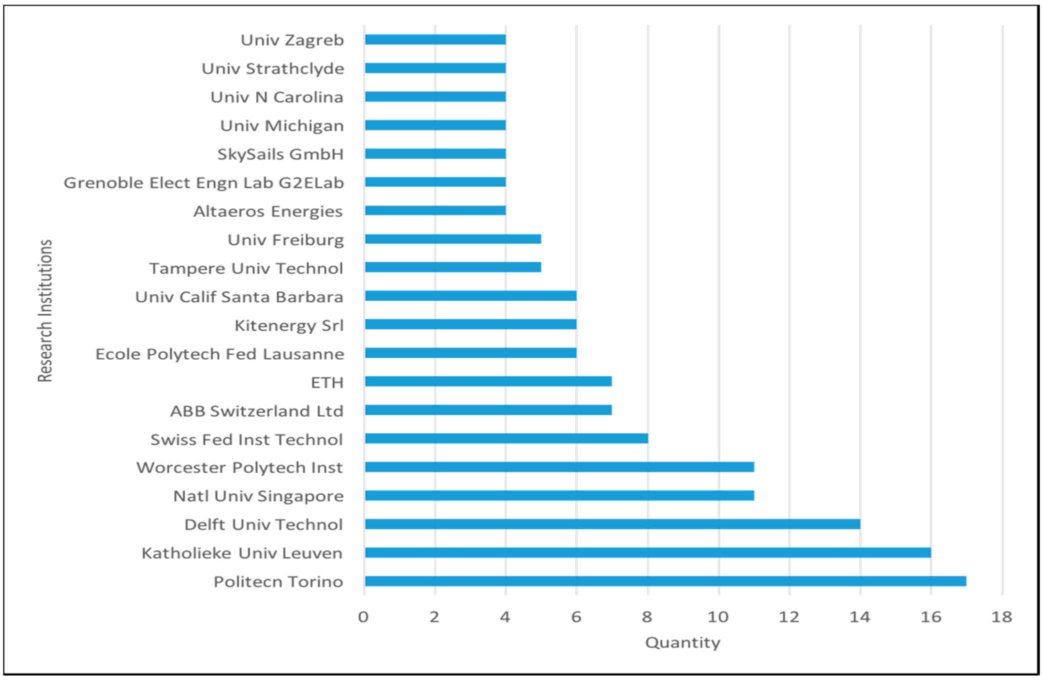

Figure 9. Top funding higher education institutions.

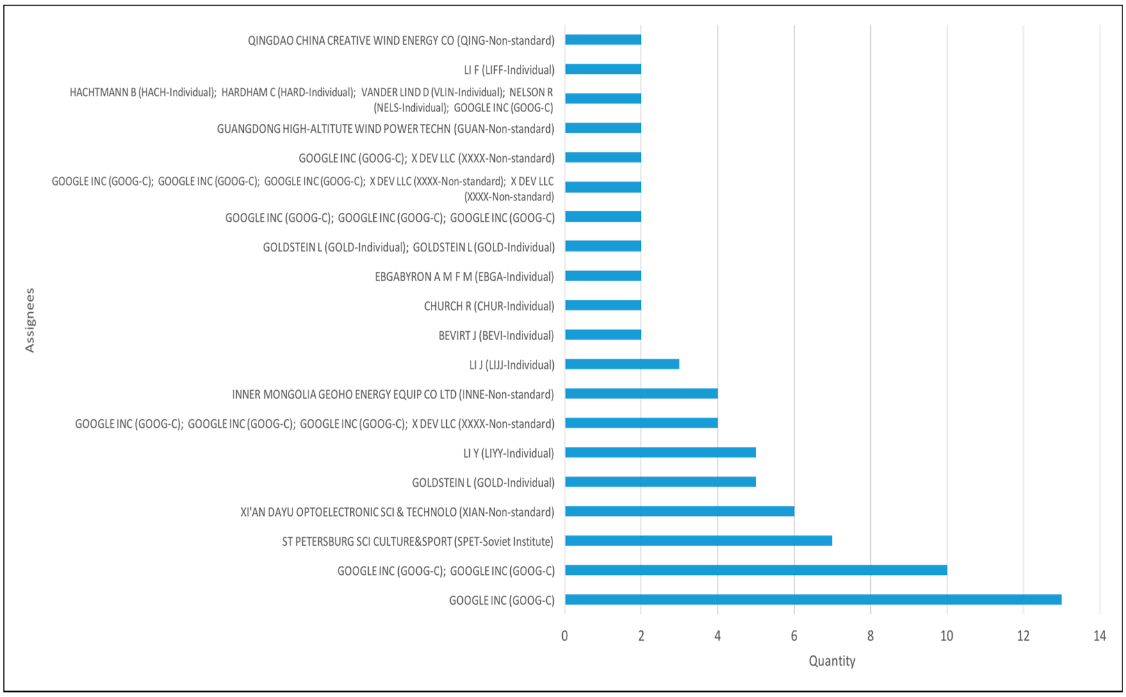

Figure 10. Top productive assignees.

Figure 10 displays the five most representative assignees; GOOGLE INC (GOOG-C); ST PETERSBURG SCI CULTURE & SPORT (SPET-Soviet Institute); XI'AN DAYU OPTOELECTRONIC SCI & TECHNOLO (XIAN-Non-standard); GOLDSTEIN L (GOLD-Individual) and LI Y (LIYY-Individual).

Figure 11 shows that the USA was the country with the highest number of papers in both scientific articles and published patents. This is because the patents come from Google Inc., a multinational online services and software company from the United States and the most visited site in the world.

The company was founded by Larry Page and Sergey Brin, both of whom were doctoral students at Stanford University, California, USA, in 1996. Google.org acquired in 2013 the American company Makani Power (Mountain View, California, USA) founded in 2006 by Corwin Hardham, Don Montague and Saul Griffith. They founded this company to exploit the unexploited wind resources more efficiently. A statement posted on the Makani Power website said that this acquisition will provide Makani with the resources needed to accelerate research to make the cost of wind energy competitive with fossil fuels and to make the development of wind-powered airborne systems a commercial reality.

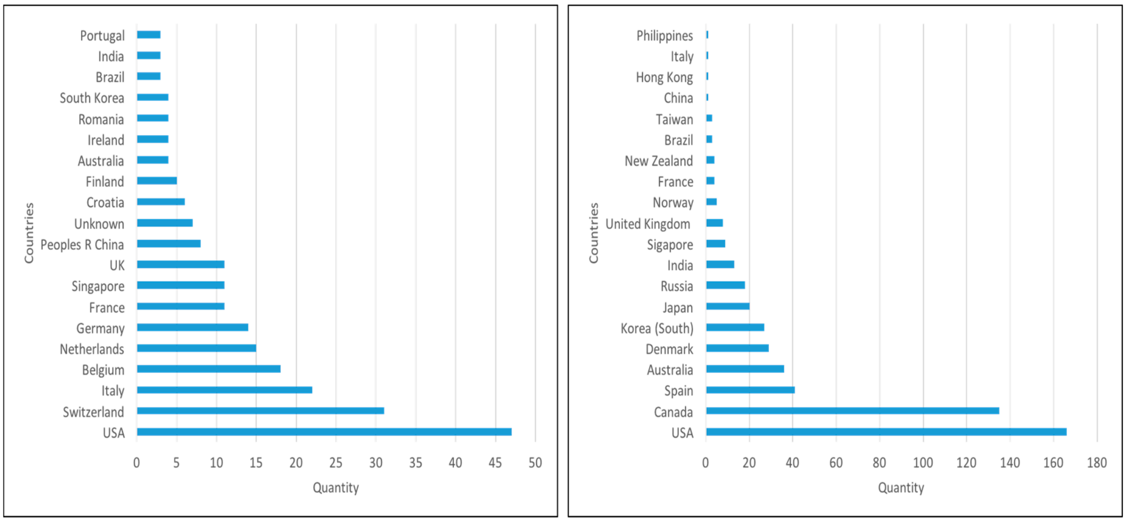

Figure 11. Top countries in terms of literature review (left) and patents (right).

In relation to the scientific publications, 47 articles were registered in the USA and they were written by the authors Fagiano, Loyd, Archer, and Goldstein.

Table 3 aims to present the most relevant articles of the sample (literature review) and its most cited references literature review. The column sample references column refers to works cited, including articles, conferences and books. The sample articles column refers to the cited articles found in the search database. Note that 14 sample articles are cited in the references (highlighted in bold). It is possible to observe that Loyd's scientific work has 98 citations, followed by the works of Canale, Fagiano and Milanese (2010) with 60 citations and the work of Ilzhoer, Houska and Diehl (2007) with 57 citations. However, it can be observed that the book "Airborne Wind Energy" by the editors Ahrens U; Diehl, M; Schmehl, R., 2013, was found in the most cited references, with 30 citations.

Table 3. Top sample literature review cited versus sample reference literature review cited.

Sample References	Citation	Sample Articles	Citation
Loyd, ML, 1980	98	**Loyd, ML, 1980**	98
Canale, M; Fagiano, L; Milanese, M, 2010	60	**Canale, M; Fagiano, L; Milanese, M, 2010**	60
Ilzhoer, A; Houska, B; Diehl, M, 2007	57	**Ilzhoer, A; Houska, B; Diehl, M, 2007**	57
Williams, P; Lansdorp, B; Ockels, W, 2008	55	**Williams, P; Lansdorp, B; Ockels, W, 2008**	55
Archer, CL; Caldeira, K, 2009	43	**Archer, CL; Caldeira, K, 2009**	43
Argatov, I; Rautakorpi, P; Silvennoinen, R, 2009	39	**Argatov, I; Rautakorpi, P; Silvennoinen, R, 2009**	39
Baayen, JH; Ockels, WJ, 2012	37	**Canale, M; Fagiano, L; Milanese, M, 2007**	37
Canale, M; Fagiano, L; Milanese, M, 2007	37	**Baayen, JH; Ockels, WJ, 2012**	37
Fagiano, L; Milanese, M, 2012	34	**Fagiano, L; Milanese, M, 2012**	34
Fagiano, L; Milanese, M; Piga, D, 2010	33	**Fagiano, L; Milanese, M; Piga, D, 2010**	33

Table 3. *Cont.*

Sample References	Citation	Sample Articles	Citation
Ahrens, U; Diehl, M; Schmehl, R, 2013	30	**Canale, M; Fagiano, L; Milanese, M, 2009**	28
Canale, M; Fagiano, L; Milanese, M, 2009	28	**Roberts, BW; Shepard, DH; Caldeira, K; Cannon, ME; Eccles, DG; Grenier, AJ; Freidin, JF, 2007**	27
Ockels, W. J., 2001	28	**Fagiano, L; Milanese, M; Piga, D, 2012**	26
Roberts, BW; Shepard, DH; Caldeira, K; Cannon, ME; Eccles, DG; Grenier, AJ; Freidin, JF, 2007	27	**Erhard, M; Strauch, H, 2013**	25
Fagiano, L; Milanese, M; Piga, D, 2012	26	Fagiano, L; Zgraggen, AU; Morari, M; Khammash, M, 2014	24
Houska B; Diehl, M, 2007	26	Argatov, I; Silvennoinen, R, 2010	18
Erhard, M; Strauch, H, 2013	25	Terink, EJ; Breukels, J; Schmehl, R; Ockels, WJ, 2011	17
Fagiano L, 2009	25	**Fagiano, L; Huynh, K; Bamieh, B; Khammash, M, 2014**	16
Fagiano, L; Zgraggen, AU; Morari, M; Khammash, M, 2014	24	Jehle, C; Schmehl, R, 2014	16
Houska, B; Diehl, M, 2006	22	Fletcher, CAJ; Roberts, BW, 1979	13

Loyd was the pioneering researcher on AWE technology. He described Crosswind Kite Power in the Journal of Energy in 1980, a concept to produce large-scale wind power through aerodynamically efficient kites. Based on aircraft, kites fly across the wind at high speed. He developed equations of motion and his calculations were validated by comparison with simple analytical models [2].

In 2010, Canale, Fagiano and Milanese provided simulations and experimental results of a new class of wind power generators, called KiteGen, in the article "High Altitude Wind Energy Generation Using Controlled Power Kites" published in IEEE Transaction Control Systems Technology. They investigated two different types of KiteGen through numerical simulations, the yo-yo configuration and the carousel configuration. For each configuration, a generator with the same characteristics was considered [65].

Ilzhoer, Houska and Diehl in 2007 investigated nonlinear model predictive control (NMPC) for control of power generating kites under changing wind conditions. The authors derived a realistic nonlinear model for a kite and compute energy optimal loops for different wind speeds, and they solved this NMPC problem numerically with the real-time iteration scheme using direct multiple shooting [66].

In 2008, Williams, P, Lansdorp, B, and Ockels, W. focused their study on the use of a light lifting body at the end of a tether to generate useful power. They studied two major configurations, the kite is used to tow a ground vehicle in the crosswind direction and the kite is flown to generate power using a ground generator. According to the authors, the numerical results illustrate that optimal power generation is most sensitive to the cycle time, tether length, and wind speed [67].

Archer, CL and Caldeira, K (2009), evaluated in the article Altitude Wind Power, the available wind power resource worldwide at altitudes between 500 and 12,000 m above ground. The authors analyzed twenty-eight years of wind data from the reanalysis by the National Centers for Environmental Prediction and the Department of Energy. These data were analyzed and interpolated to study geographical distributions and persistency of winds at all altitudes [68].

Figure 12 shows the 19 most cited patents. The top five patents are: US20120104763-A1 (32 citations), US20130221679-A1 (26 citations), US20110260462-A1 (24 citations), US6254034-B1 (23 citations) and US20100295303-A1 (19 citations). They are described below.

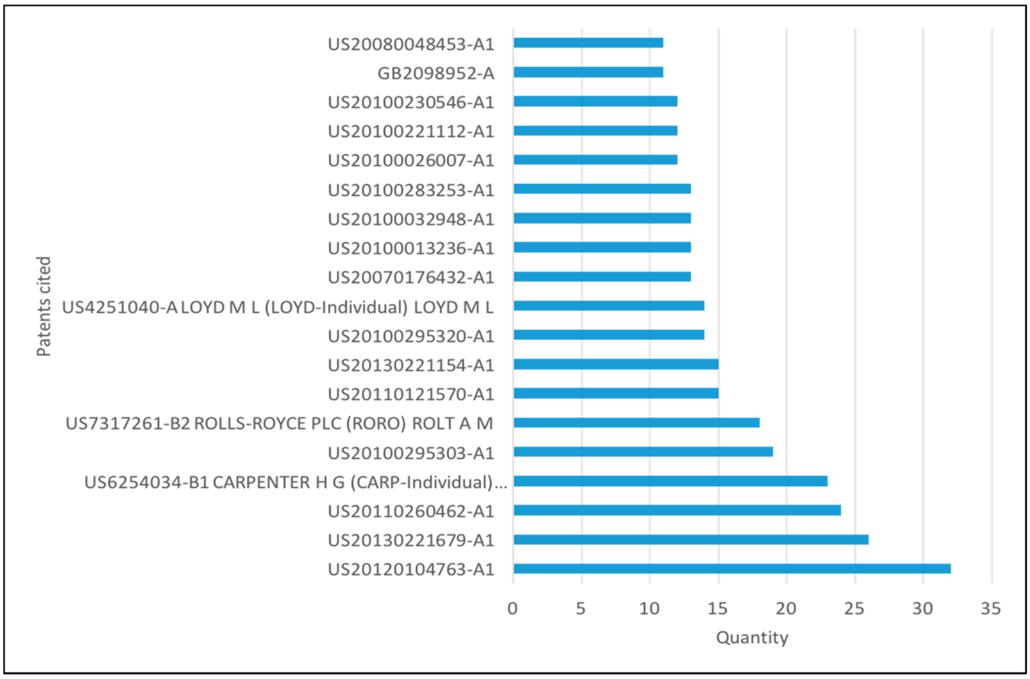

Figure 12. Top patents cited.

US20120104763-A1 was published in 2012 by Vander Lind, entitled Kite configuration and flight strategy for high wind speeds [69]. It describes a crosswind kite system adapted to operate in an alternate mode in high winds. The system may operate at reduced efficiency in high winds to moderate loading on the system during those high winds. The system may use multi-element airfoils that are actuated to reduce the coefficient of lift of the airfoils to moderate loading in high wind conditions. Other flight aspects may be controlled, including flying the crosswind kite in side slip to induce drag which may lower overloading on the system.

US20130221679-A1 was published in 2013, by Damon Vander Lind, entitled Kite Ground Station and System Using Same, and deals with kite system with a ground station adapted for airborne power generation [70]. The kite system may include a kite that comprises one or more airfoils which have mounted thereon the plurality of turbine driven generators. The turbine driven generators may also function as motor driven propellers in a powered flight mode, which may be used during takeoff, and may include aspects of vertical takeoff and landing. A perch adapted to facilitate the takeoff and landing may be used as part of the system. The perch may pivot such that the pivot is oriented towards the tension direction of the tether.

US20110260462-A1 was published in 2011 by Damon Vander Lind, entitled Planform Configuration for Stability of a Powered Kite and a System and Method for Use of Same [71]. It discusses system and method of power generation, wind-based flight, and takeoff and landing using a tethered kite with a raised tail mounted rearward of the main wing or wings. The tail may be fully rotatable and may be rotate more than 90° from its nominal position during a traditional flight paradigm.

US6254034-B1 was published in 1999 by Howard G. Carpenter, entitled Tethered aircraft system for gathering energy from Wind [72]. It discussed the tethered aircraft of the system is blown by wind to travel downwind at a controlled rate for maximal mechanical energy gathering from wind whose velocity fluctuates and gusts. A cycle of travel is completed when the aircraft is travelled upwind to the site of the beginning of downwind travel in which downwind travel is recommenced. The downwind travelling aircraft pulling unwinds its tether from an anchored windlass drum to spin the rotor of an interconnected electrical machine to convert the mechanical energy to electricity.

US20100295303-A1 was published in 2009 by Damon Vander Lind, Becker Van Niekerk, Corwin Hardham, entitled Tethered system for power generation [73]. It discusses a system for power generation comprising a wing, a turbine, a tether, and a tether tension sensor. The wing is for generating lift. The turbine is coupled to the wing and it is used for generating power from rotation of a propeller or for generating thrust using the propeller. One end of the tether is coupled to the wing. The tether tension sensor is for determining the tension of the tether.

Figure 13 shows the frequency of common keywords that appeared in patents and articles related to wind energy with tethered airfoils. We noted that, in both searches, the words wind energy, and airborne wind energy are found. This allowed us to validate the adherence of the keywords used in the selection of research articles and patents to those found in the *Web of Science* and *Derwent Innovation Index* databases.

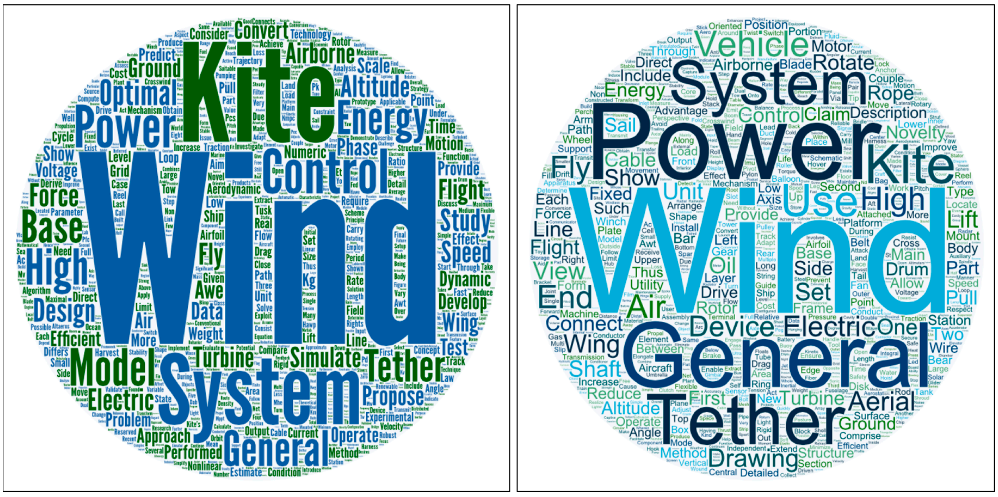

Figure 13. Top keywords by authors of literature review abstracts (**top**); and top keywords appearing in patent abstracts (**below**).

In this study, it was possible to perform the authors network analysis, as shown in Figure 14 for literature review and Figure 15 for patents. Figure 14 shows the network of collaboration among authors of scientific articles found in the literature review search. It displays the presence of 57 clusters with 294 items and their connection with 555 links. It was observed that the clusters formed agree with the information presented previously by the authors who stood out with the most published works in the area and highest number of citations. The most representative clusters are in blue, red, green, light green, dark green, pink, purple, and yellow.

The blue cluster consists of 12 authors who work together. In this cluster, Fagiano, Milanese, Canale, Novara, Razza, and Piga are the most prominent figures. This cluster is directly linked to the beige cluster (nine authors) in which Zgraggen, Morari and Khammash stand out and with the light purple cluster (four authors) consisting of Argatov, Rautakorpi, Shafranov and Silvennoinen.

The red cluster consists of 20 authors who form a collaboration network. The authors who are most prominent in this cluster are Diehl, Gros, Zanon, Houska, Horn, Swevers, Geebelen and Vukov. This cluster is linked to three other clusters: the light blue cluster (six authors) in which Ahmad, Coleman and Toal stand out; the brown cluster (six authors) in which Williams, Lansdorp and Ruiterkamp stand out; and the gray cluster (two authors) in which Erhard and Strauch are the most prominent authors.

The yellow cluster consists of 14 authors who are related to each other. These authors are Vermillion and Kolmanovscky, who are directly linked to the cluster of authors such as Cherubini, Fontana, Papini and Vertechy.

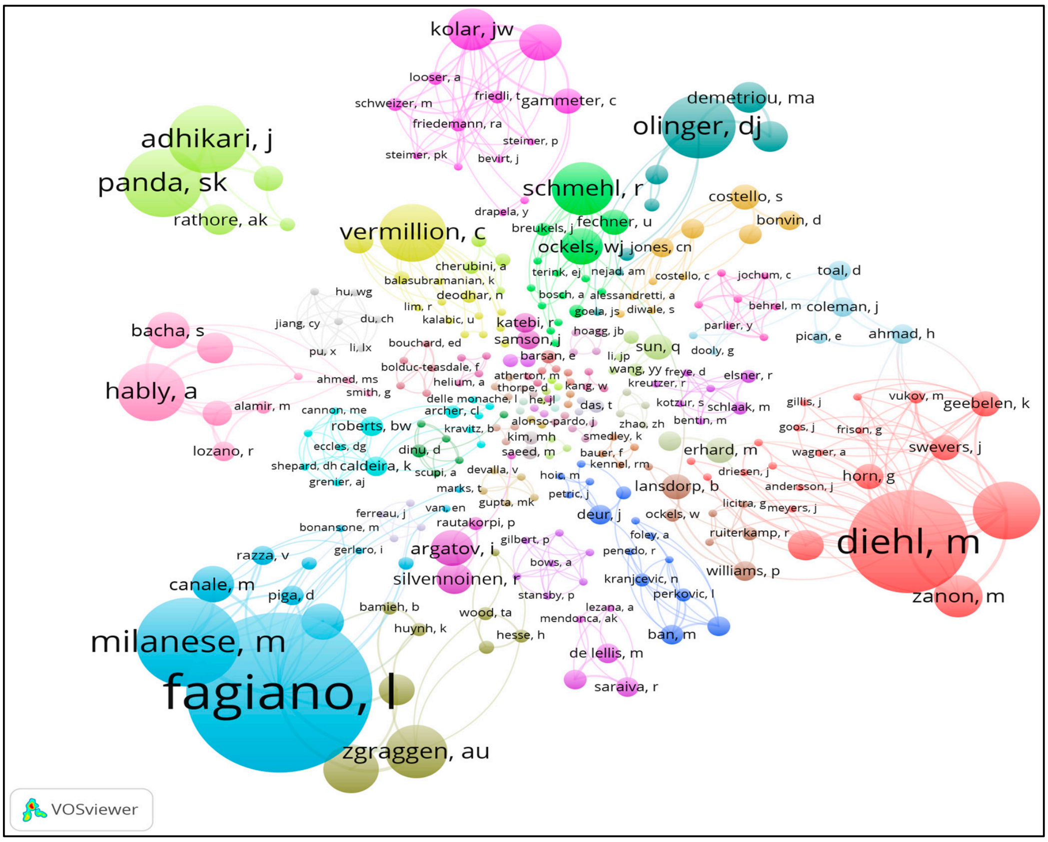

Figure 14. Network analysis of the scientific literature.

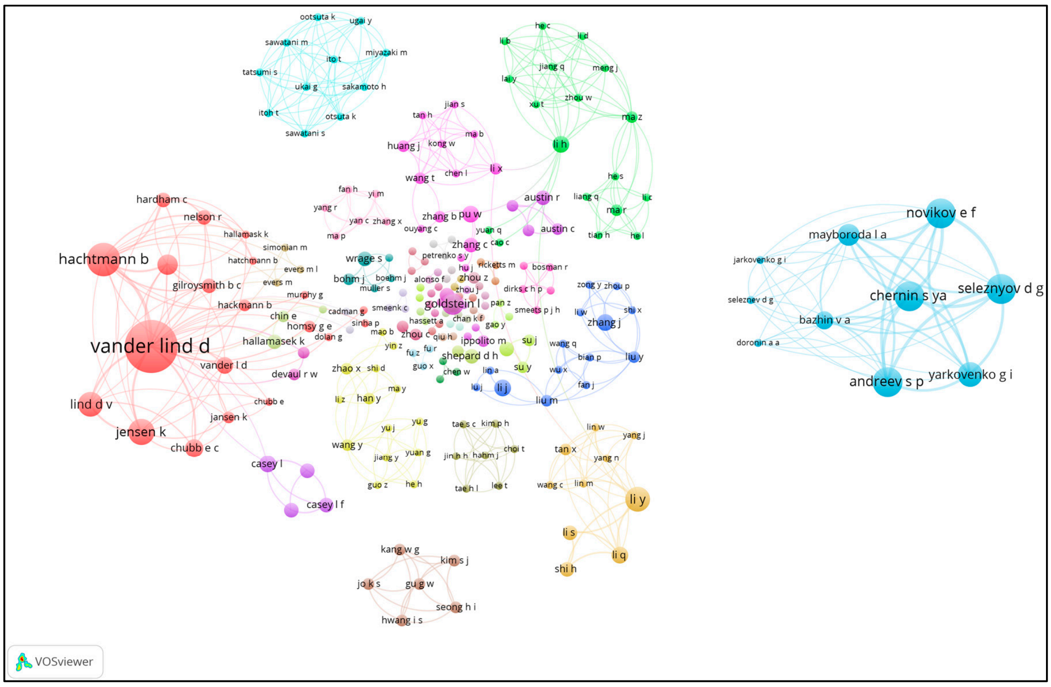

Figure 15. Network analysis of the patents.

As for the green cluster, it consists of 15 prominent authors, such as Schmehl, Ockels and Fechner. This cluster is directly related to the dark green cluster (eight authors), consisting of Oliger, Li, Demetriou, Tryggvason and Ghasemi. This cluster in turn is linked to the beige cluster (10 authors), including authors such as Costello, Bonvin, Jones, Francois and Lymperopoulos.

On the other hand, one can observe that the light green cluster does not make any connections with any author collaboration network. This cluster consists of five authors: Panda, Adhikari, Poraj, Prasanna and Rathore.

Another cluster that is not related to any author collaboration network is the purple cluster, consisting of 13 prominent authors, including Kolar, Krismer, Looser, Gammeter and Friedemann.

Finally, the pink cluster consists of nine prominent authors, including Hably, Lozano, Bacha and Dumon. This cluster is not directly related to any other cluster of author collaboration network.

Figure 15 shows the collaborative network among patent inventors. The figure displays the presence of 107 clusters with 284 items and their connection with 523 links. It is possible to observe that the cluster goes in the opposite direction of the information presented previously about the inventors who stood out with the greatest number of patents in the area.

It becomes evident in Figure 15 that four clusters are not linked to the patent inventors' collaboration network. These clusters are brown cluster (six inventors) with Kang, Kim, Seong; blue cluster (11 authors) featuring Sawatani, Otsuta, Ito, and Miyazaki; light blue cluster (10 authors) represented by Andreev, Chernin, Novikov, Mayboroda and Yarkovenko; and beige cluster (seven authors) with Choi, Hahm, Kim, Lee and Tae.

On the other hand, the most representative clusters in the collaboration network are: red, purple, beige and green clusters.

The red cluster is made up of 30 inventors, most notably: Vander Lind, Jensen, Hachtmann, Lind, Hardhan and Gilroysmith. This cluster is directly related to the purple cluster (two inventors and four patents) with Casey and Goessling.

The beige cluster consists of 10 inventors who are represented by Li Y., Li Q., Yang, Wang and Tan. This cluster is directly related to the blue cluster consisting of 14 inventors, among them the most prominent ones are Zhang, Liu, Zhou, Bian and Fan.

The green cluster is directly related to the dark purple clusters (four inventors), in which the most prominent inventors are Austin and Mercier. The light purple cluster (14 inventors) is represented by Pu, Zhang, Wang and Huang. These purple clusters are connected respectively.

Finally, it can be noticed that the inventor Goldstein presents seven patents, which in turn makes him the most representative in his network (dark red cluster), however, it is important to note that he is not relating to other inventors.

In this sense, we validate the data about the authors presented previously and the inventors considered representative and pioneers in wind energy with tethered airfoils.

5. Conclusions

In this article, we offered a brief overview of the scientific and technological progress of research on wind energy with wired airfoils, focusing both in academic and industrial activities. A total of 477 documents (239 scientific papers and 238 patents) were collected from the *Web of Science* and the *Derwent Innovations Index*. Those documents form the sample of this research.

By means of the bibliometric analysis, it was possible to identify that researches on wind energy with tethered airfoils began their activities in the late 1970s and the first patent found was in 1975 by inventors Dai, C. and Dai, J. The first scientific publication was in 1979 by authors Fletcher and Roberts, and in 1980 by Miles L. Loyd.

The most representative and cited authors on the subject were Fagiano, Milanese, Ockels and Schmehl. Additionally, the inventors who submitted more patents were Vander Lind, Hachtmann, Goldstein and Jensen. They work for the company that has more patents in this sample, Google Inc. The most representative research institutions are Politecnico Torino, Katlolieke University Leuven, Delft University Technology, National University Singapore and Worcester Polytech Inst. The United States is the country that presented the highest number of patents and scientific works, since the company with the most patents and the most productive authors of the subject are from this country or have already developed research in this country.

Journals are the main source of scientific articles. The most important journals were Airborne Wind Energy (book), Renewable Energy, American Control Conference (ACC), IEEE Transactions on Control Systems Technology, and American Control Conference (ACC). The technology classes were in accordance with the CPI (Chemical Patents Index)—classification used by the Derwent Innovations Index. The patents for this research are in classes X15, Q54, W06, Q25, and P36, which are in the Green Technology area. Finally, we noticed that both scientific works and patents set up collaboration networksl that is, the authors interact with each other to establish collaborative partnerships.

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Conflicts of Interest: The authors declare no conflict of interest.

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