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Article

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Research paper

Forecasting of wind energy technology domains based on the technology life cycle approach

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ABSTRACT

Wind energy technologies are being developed in order to reduce the costs of the generated electricity and increasing technological performance. Therefore, understanding the technological development paths is an important part of the debates among technology developers and policymakers of energy systems. Due to recognize the wind technology orientation, the published patents in wind technology have been analyzed. Five groups of technology have been found, and the result of technological trends and life cycles for each one has been discussed. In order to clarify the main issues in each technology domain, a cluster dendrogram of frequent keywords in each domain through text analysis has been drawn. Text analysis of all published patents illustrated that controlling pitch and larger blade design are the most frequent words in the “blades and rotor” and “control of turbines” domains respectively. Two main domains of technology have been considered a lot in patents, “blades and rotor” and “control of turbines”. In the next step, the technological life cycles of all five domains have been discussed. In spite of the number of published patents in “blades and rotor” and “control of turbines” domains, “nacelle” is in the maturity stage.

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1. Introduction

Due to fast growth in population, economy, and urbanization around the world, the demand for energy is facing a massive growth (Baloch et al., 2016; Razmjoo et al., 2019). When 2016 came to an end, the total amount of electrical energy was 24353 TWh worldwide, and this was about four times bigger in comparison to the 6131 TWh used the year 1973. Currently, the primary source of electrical energy produced is fossil fuels, and 80% of the entire investment of the global energy supply goes to traditional oil, gas and coal energy (IEA, 2017; Yearbook, 2017). According to the literature, the usage of renewable resources for generating electricity is the most promising key to meet future energy needs from the sustainability viewpoint (Armin Razmjoo et al., 2019).

Moreover, wind energy has been recognized as a secure and reliable low-carbon technology (Qin et al., 2015; Tahani et al., 2017). In recent decades, the problem of environmental issues and greenhouse gas emissions have been one of the greatest concerns of humanity (Mondani et al., 2017; Mehrpooya et al., 2018). These problems are not just specific to a country, but

it is a worldwide problem that accompanies a variety of issues. At present, utilizing wind energy as the main source of energy is arising exponentially in the world which shows the growth of its importance and applicability. Therefore, the wind is considered as one of the satisfactory renewable resources to generate electricity due to its low cost compared to others and its advantages (Razmjoo and Davarpanah, 2019; Şahin, 2004). Wind energy, having no emission which is vital for the environment, is one of the cleanest forms of energy. Currently, using wind energy is mainly associated with converting it into electricity (Shanker and Singh, 2012; Ehyaei et al., 2019).

When we consider the importance of wind energy, we realize that if politicians and investors had acceptable knowledge about different technologies, their market and of course the economic potential of them, then they could be able to see investment opportunities and use them. In a corporative strategy, the decision-makers have to identify and choose the right technology at the right time which is of great importance, while potential abandoning of new technology can result into an enormous financial loss (Hashemi et al., 2018; Bakhtiar et al., 2019).

This study is supposed to undertake this issue by using patent analysis and technology life cycle which are the most reliable and credible tools of technology evaluation and forecasting. First, we need to explain the concept and the major technologies of wind

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energy at a general level. After that, the patent registration data and the search direction of each technology have to be gathered from reliable and proper sources. Following that, the extracted patents have to be analyzed. To conclude, the life cycle of each technology is drawn.

2. Literature reviews

The process of converting wind or the flow of air to electrical energy that happens naturally in the earth's atmosphere is called wind energy. While wind turbine has some unanticipated environmental impact (Dai et al., 2015; Saidur et al., 2010; Ehyaei and Bahadori, 2006), like noise, compared to fossil fuel, it is more eco-friendly. Because of the energy requirement that leads to the immoderate exploitation of traditional sources like coal, petroleum and natural gases, carbon dioxide is increasing, and it is expected to reach 36 billion metric tons worldwide in 2020 (Outlook, 2013).

Types and classification of wind energy (AWEA, 2017):

- **Utility-scale wind:** This type consists of wind turbines that are diverse in capacity from 100 kW to several megawatts, in which electrical energy is carried to the power grid, and using electric utilities or the operators of the power system; it can be distributed to the end.
- **Distributed or “small” wind:** it includes a small and single wind turbine which is below 100 kW and is mostly used to power a house, farm or small business and does not have any connection with the grid.
- **Offshore wind:** wind turbines which are constructed in vast bodies of water and are usually on the continental shelf. Offshore wind turbines are always greater in size than the urban turbines and can generate more electricity.

2.1. Downstream technologies of wind energy

Wind energy is utilized in two different ways: directly or indirectly by converting it into electricity. The wind turbine is the most important part of the wind energy conversion system (WECS) that is used to capture the physical energy of wind and convert it to mechanical energy by rotating the rotor of the generator, using the help of the gearbox (Viveiros et al., 2015). Producing electricity is by exploiting the plentifully available wind energy became possible only after the emergence of a wind turbine (Kaldellis and Zafirakis, 2011). A detailed view from the inside of a wind turbine, the different parts of it and also its serviceability is shown in Fig. 1. due to the development of some special types of generators together combined with the power of electronic devices, the possibility of making gearless turbines has emerged (Hansen et al., 2001).

Wind turbines are generally two types: the horizontal-axis type model (HAWT), and the vertical-axis type model (VAWT) (Suffer et al., 2014). Because of their greater efficiency, HAWTs are more preferred in the wind industries. Though they possess lower efficiency compared to HAWTs, VAWTs can capture the wind from any direction (Aziz et al., 2014). Also, they have a lower cut-in speed which allows them to generate electricity even in low wind speed. The VAWTs are largely effective if they are used in small numbers such as on a rooftop (Shah et al., 2018). In the past few years, there has been an increase in attention in using offshore wind resources (Cheng et al., 2017). Thus, the commercial development of floating horizontal axis wind turbines (FHAWTs) and vertical axis wind turbines (FVAWTs) has also seen an increase. A wind turbine generally consists of different components and subsystems such as a generator, rotor hub and blade, gearbox, and a tower (Qiao and Lu, 2015).

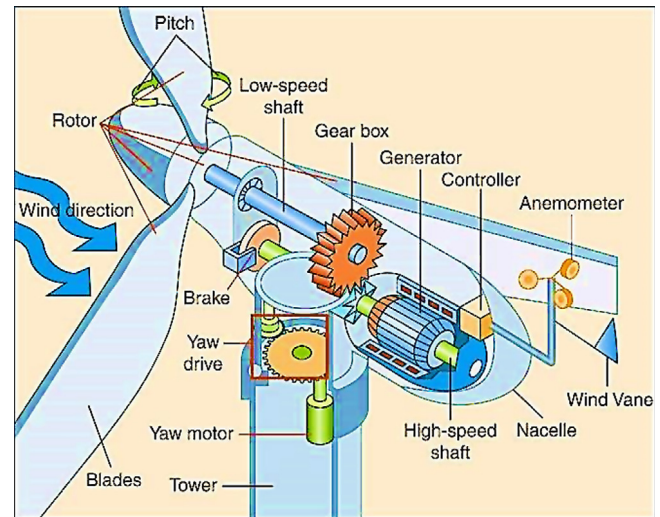


Fig. 1. Inside of a wind turbine.

All the major parts of a wind energy system are shortly explained below (W. D. C. U.S. Department of energy, 0000; Jha, 2017):

• Nacelle:

It is put on the top of the tower and contains the gearbox, low and high-speed shafts, generator, controller, and brake. Some nacelles are big enough that a helicopter could land on them.

• Rotor Hub and Blade:

The rotor is made with blades and a hub. The interaction between wind and rotor is responsible for the production of power due to the wind turbine. The blades are lifted and rotated when the wind is blown over them which makes the rotor to spin. Most turbines usually have either 2 or 3 blades. Another part of the rotor is pitch drive that we use it to keep the rotational speed of the blades at a favorable operational range of 1000–3600 RPM, that prevents the rotor from turning in too high or too low winds to generate electricity.

• Gearbox:

The two main parts of the gearbox include gear and bearings. It connects the low-speed shaft to the high-speed shaft and increases the speed of rotations from about 100 RPM to near 1000–3600 RPM. Most generators need a rotational speed of this amount to produce electricity.

• Electric generator:

A generator converts the mechanical energy of the wind turbine rotor into electrical energy. While WECS is using different types of generators (Polinder et al., 2006). double-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) because of their reliability and efficient capturing of wind are getting the main attention (Bennouk et al., 2018). A wind turbine that uses a concurrent generator is typically considered as gearless or direct drive wind turbine generator system. Recently, the PMSG (Geng and Xu, 2011), that is supported with full power electronics conversion system (Fig. 2(b)) has been getting a significant amount of attention to producing power from a gearless wind turbine. PMSG possesses a magnetic field which is produced by a permanent magnet. Thus, it is not necessary to have a dc source for incitement. PMSG has received much focus because of its self-excitation capacity. Using the induction generator as wind turbine generator has had increase due to its brushless generator, superior dynamic response, simple operation and lower price (Mesemanolis et al., 2013). To operate, the induction generator needs reactive power to be fed so that it could

power the magnetic field. The grid generates the essential power for induction generator. Although in a standalone use, the need for the reactive power is met by external sources, for instance, power electronic converter or bank of capacitors. The connection between the capacitor and the induction generator is called a self-excited induction generator (SEIG). Currently, DFIGs have been widely applied in wind technology due to their advantageous features, such as cost-effectiveness, flexibility, and controllability of power flow (Falehi and Rafiee, 2018). The rotor cycle of DFIG (Fig. 2(a)) is connected using an external variable voltage through slip rings and can be controlled by a device from outside to attain variable speed operation (Farret and Simoes, 2006). The stator of DFIG is connected to the grid using a transformer while the rotor is connected to it using a harmonic filter (Kaloi et al., 2016). The DFIG can function around 30% above or below the concurrent speed that is sufficient enough for normal speed variation. This unique feature makes DFIG become able to capture a big part of the market (around 50%) as a wind generator. Nowadays many are doing experiments on devices that are superconductor based power. Using high-temperature superconductor (HTS) direct-drive generator, we can reduce the size and weight by a large amount (Snitchler et al., 2011). A general scheme for WECS that shows different parts and systems is shown in Fig. 3.

● Controller:

For the electric power drawn from wind energy to be effective, WECS plays the most crucial role. It starts the machine when wind speed is about 3.5 to 7.5 meter per second (m s^{-1}) and shuts it down when the wind speed is about 25 m s^{-1} due to the possibility of being damaged while working at a speed above 24 m s^{-1} , turbines stop working. The control methods and techniques are used in different parts and subsystems of WECS (Tiwari and Babu, 2016). Various control strategies in WECS and detailed configurations are shown in Figs. 4 and 5.

● Aerodynamic control (pitch control)

In pitch angle control, in order to control its speed and aerodynamic power, the turbine blade angles are changed. Thus, it is vital for variable-speed wind turbine conversion systems (Agarwala, 2019). Also, it seems to it that the mechanical safety of the wind turbine when a sudden gust happens.

● Maximum Power Point Control (MPP)

A much desirable feature of wind turbine system (WTS) is its ability to function at MPP under varying wind speed. By drawing the maximum possible energy from a wide range of wind speed values, the MPPT algorithm enables WTS to maximize its efficiency. Many MPPT theories are developed recently with decisive concern as for how to extract maximum power from wind at any distant effectively (Cheng et al., 2017).

● Grid side and machine side controller

The machine side controller (MSC) makes WECS be able to operate various speeds. It captures the highest energy amount that is possible by varying wind speed. MSC changes the speed of the rotor in order to achieve maximum power and increase the system's stability. Grid side controller (GSC) is helpful in improving the quality of generated power, grid core compliance and synchronization of the whole system with the grid. It is a useful tool to draw active power control. GSC plays no role in power conversion or generated use. It is generally responsible for the quality of the generated power and synchronization. Voltage oriented control (VOC) and Direct power control (DPC) are the two groups forming GSC.

● Tower and foundation:

The tower is made from tubular steel, steel lattice or concrete and it supports the structure of the turbine. Due to the fact that the wind speed increases with height, the taller the towers get, the more capacity they will have to generate more electricity. The structures mainly used in offshore wind energy

projects are gravity-based foundations, monopiles and tubular metallic foundations (tripods and jackets) (Esteban, 2009). Each type has different features which allow them to become suitable for various applications:

1. Gravity base: these are shallow foundations that are capable of maintaining the stability for any condition due to the weight of the structure. Because it is necessary to prepare the seabed, thus they are not suitable for depths of over 10 m.

2. Monopiles: these are single deep metal foundations through penetrating the ground, they are able to transmit their load to it. Their installation is easy, and seabed preparation is not necessary. Their usage is limited to less than 30 m depths.

3. Tubular metallic foundations: this group includes jacket and tripod foundations. Their characteristics are similar; the only difference being that the jackets have four legs and tripods three. This makes them suitable for depths of more than 20 m (Ashuri and Zaayer, 2007).

Tripiles and the floating structures are less used or under-developed foundations. Tripiles are based in three steel tubes that a crossed tripod is supported on the top of them. Floating structures are made by a platform and a mooring system with various possible typologies (Colmenar-Santos et al., 2016). There are various methods for technology forecasting and life cycle analyzing. Daim et al. (2006) forecasted three new technologies by using patent and bibliometric data and system dynamic models, which are fuel cells, optical storage technologies and food safety. The other research Daim and et al. used the World Intellectual Property Organization (WIPO) and Science Direct as sources for patents and papers for forecasting technology in the energy storage sector in future electricity generation. Multiple patent indicators methods were employed to derive a model by Gao et al. (2013) for estimating technology life cycle analysis. In the first step, the patent technology life cycle has been assessed and then validated the model with the technology with the identified life cycle. In the other research to forecast the technology states, four criteria were used by Altuntas et al. (2015). One of the criteria was the technology life cycle which is estimated by S-curve. Gallego et al. (2008). using the Delphi method to conduct open software program for technology forecasting.

3. Technology Assessment (TA)

The climate change mitigation cost in the future is heavily dependent on technological changes that happen (Pizer and Popp, 2008). Technology assessment is somehow a cognitive tool that helps to understand the long-term patterns of innovation in energy technologies better, so it is vital for technology forecasting and the policies made about climate change in public. The studies that are done on Technology assessment can be used in three different ways, and each one is applicable in its specific context: the first way or approach is about TA studies that are focused on a typical project, directly organized in the areas that are closely related to the uses of a type of technology. One other would be TA studies that are focused on any particular technology that is studying viewpoints related to it and its influence on the environment, industry and human society to the extensive areas of its uses, now or in the future. The last approach is about the TA studies focused on a particular program (Khodayari and Aslani, 2018). This approach indicates very differently innovation and learning processes in the field of energy technology and the need for adapting the policies of technology to its characteristics. Meanwhile, they are helpful in conceptualizing the former unfinished evident about the effect of technology policies in the past. These are the studies that try to find and analyze the possible choices and technical solutions for the problems related to different issues such as transportation, energy provision and environmental issues (Huenteler et al., 2016).

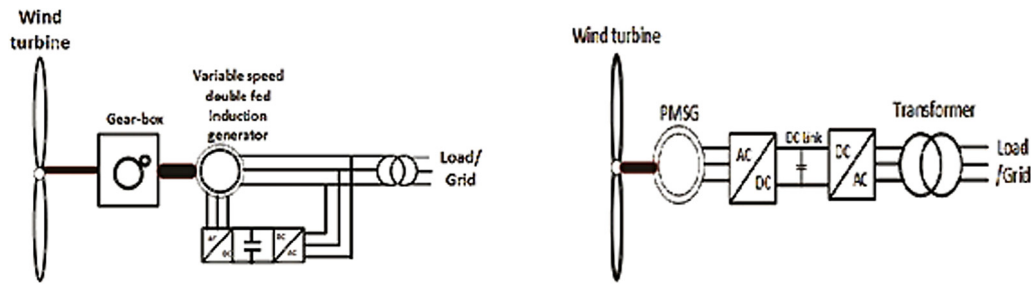


Fig. 2. (a) Variable speed DFIG with power converter (b) Variable speed PMSG with power converter (Jha, 2017).

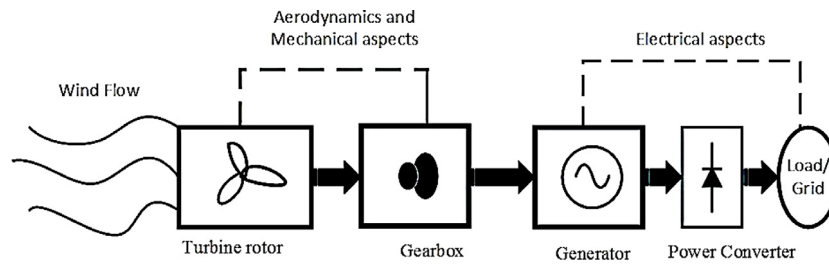


Fig. 3. The general scheme of the wind energy conversion system (Jha, 2017).

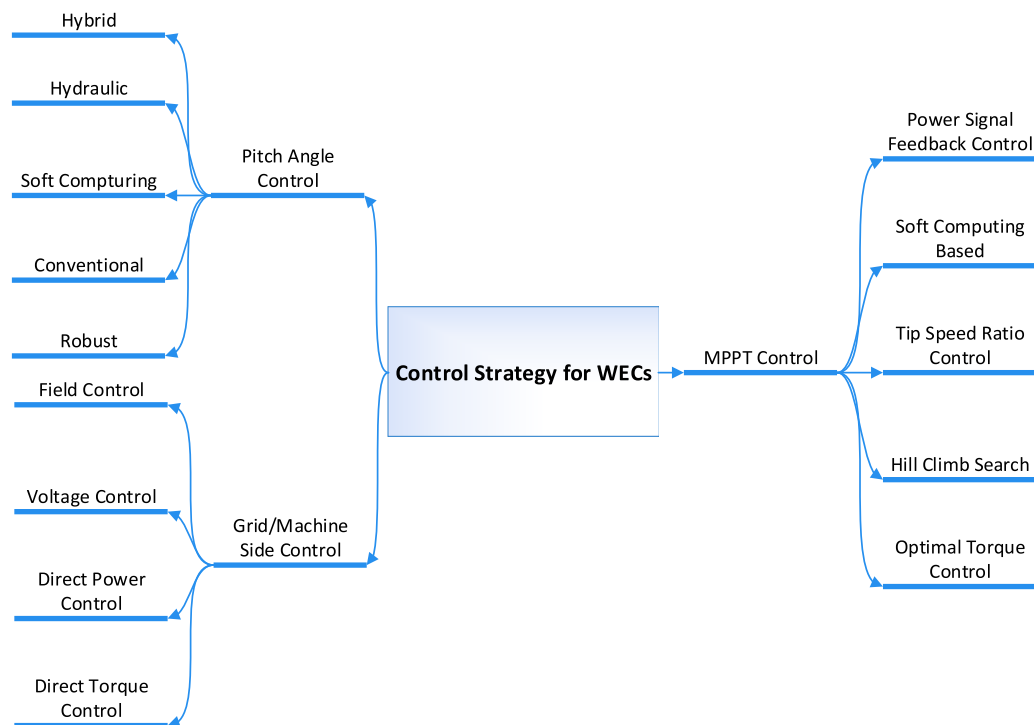


Fig. 4. Different control strategy in WECS.

Source: Adapted from Jha (2017).

3.1. The technology life cycle

The progress of technology “is slow at the beginning, then quickly gets faster and finally declines which is inevitable” (Foster, 1988), thus similar to the general form of an S-curve this is defined in a number of phrases such as ‘embryonic’, ‘growth’, ‘maturity’ and ‘aging’ (Çetindamar et al., 2016).

On the other hand, we can use this to analyze the change in performance or the rate of technology improvement throughout the time (Foster, 1988; Dehghani Madvar et al., 2019). in here we can see that due to the fundamental struggles about the

uncertainties of this technology, the improvement rate is slow, but when those obstacles are solved it gets faster, and finally it slows down again because the possible limits of the technology are passed (Jamali et al., 2016; Aslani et al., 2018). Although experimental evidence is widely used, it has caused some doubts about the validity of the performance compared to time S-curve suggesting vast performance improvements happen after a long time of not having any improvement, rather than to a smooth S-curve (Sood and Tellis, 2005; Taylor and Taylor, 2012). Fig. 6 has shortened this discussion and shows typical forms of the S-Curve.

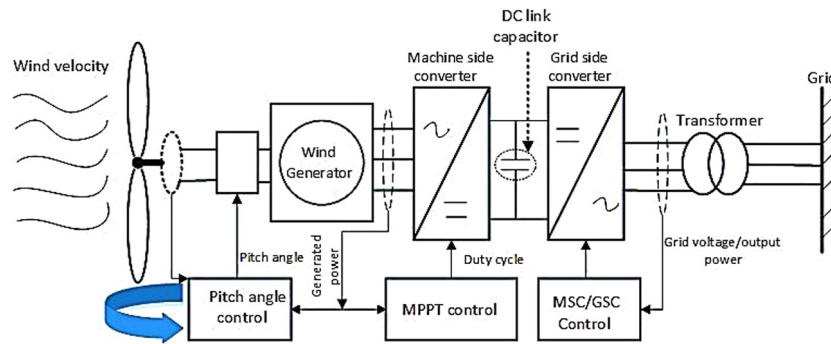


Fig. 5. WECS with different control subsystem (Jha, 2017).

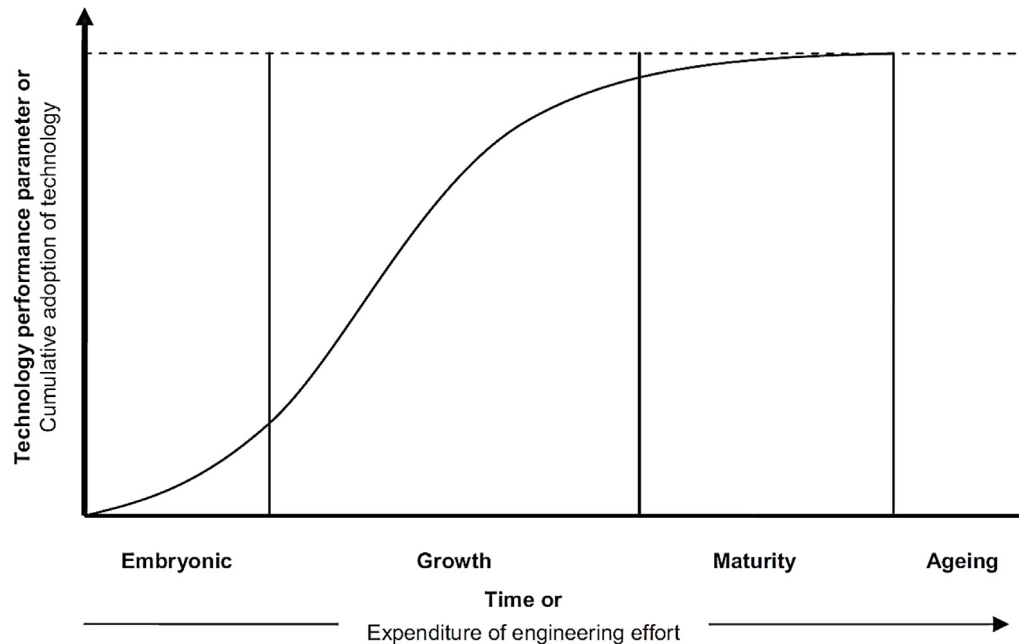


Fig. 6. Typical technology S-curve.
Source: Adapted from Cetindamar et al. (2009).

3.2. Patent analysis

Patents besides technological gain have economic value. Firms and companies for protecting their technologies should patent them (Madvar et al., 2016; Dehghani Madvar et al., 2018). While patenting technology is an expensive procedure, the technology should have remarkable value. Hence analyzing patent can provide significant information about the technologies. Analyzing the data of each section of wind power technology would be helpful to identify the focal point of the technology.

Regarding the number of patents in the specific part can demonstrate the importance of that section (Madavar et al., 2017). Deep investigation in the extracted patents in the particular sector of technology will indicate the major issue of that sector. Finding the hot area in each part of technology can be feedback for policymakers and researchers. The R&D expenditure, which will be allocated to the particular technology, requires hindsight and vision. Answering “What is going on through the future of technology” always is amazing and helpful.

4. Research methods

Recognizing and identifying the trends of sub-technologies of wind energy could be helpful to establish applicable policies.

Governmental subsidies should be assigned to an appropriate technology sector; therefore, this recognition can pave the way. The research method would be considered descriptive and in the aspect of the goal is considered developmental. The patents of each technology related to wind power are extracted from an online patent database.¹ In order to accurate the result, patent searching has been done first by keywords. The extracted patent then pre-analyzed and the key codes are refined. Then the target patents have been extracted. The research frame is illustrated in Fig. 7.

As is obvious in Fig. 7, patents will be analyzed after increasing the accuracy of data. The investigation in this research has been held on patent from January 1973 to December 2018. The number extracted patent is 76307. The main issue in extracting patent, after accuracy, is the comprehensiveness of data. To overcome this challenge the well proved Patentinspiration is used (Dehghani Madvar et al., 2019; Jamali et al., 2016; Dehghani Madvar et al., 2018; Madavar et al., 2017; Ahmadi et al., 2019). This online database which gathers patent data from more than ten authorities.

¹ <http://patentinspiration.com/>.

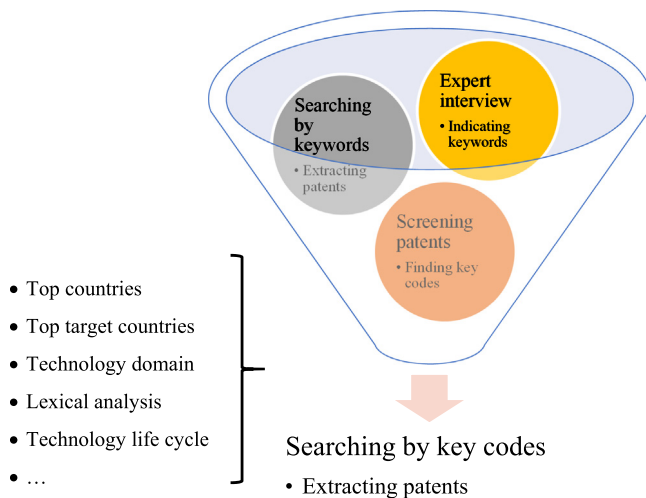


Fig. 7. Research steps.

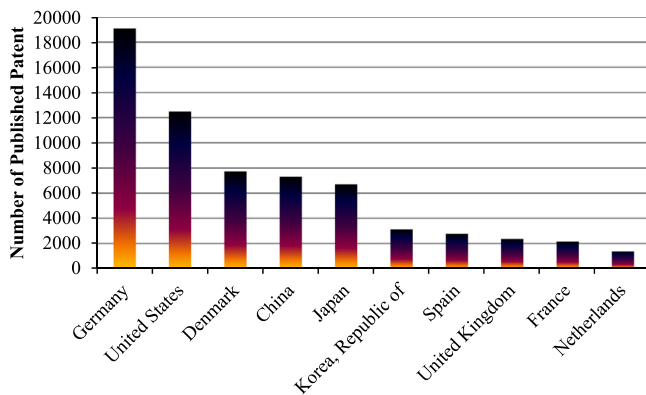


Fig. 8. Top ten countries in publishing wind technology patent.

5. Result and discussion

To secure the energy demand in the future, the countries must transmit to more renewable resources, besides environmental concern which has been raised globally. Wind power is considered as one of the comprising energy resources to face the energy challenge on supply and demand. Countries government plan in energy security can be identified by determining their renewable energy technological orientation. The R&D activities as it is mentioned earlier can be indicated as a patent. While a country has published vast of patents in a specific technology domain, the R&D expenditures have spent to that area. Therefore, the top ten countries with the high amount of number published patents are shown in Fig. 8.

The highest number of the published patent in wind technology is related to Germany with 19071 patents, so far. The United State is the second country with the highest published patent with 12486 patents following by Denmark and China with 7717 and 7307 published patents respectively. The Asia region contribution to developing wind technology is remarkable. China, Japan, and South Korea have the highest published patent in the Asia region. Although Japan is the second major player in wind technology after China in Asia, India is the second biggest electricity supplier through wind technology. The major part of the Asian market will be dominated by India in the foreseeable future and India will play a remarkable role in the next decade (GlobalWindEnergyCouncil, 2017). In order to eradicate

poverty, India requires meeting sustainability in various sectors such as economic and energy. The comprehensive and broad policy should be implemented by India to establish sustainability. The Indian policy to promote wind energy includes different types of incentives and fund (Sholapurkar and Mahajan, 2015). Total install capacity of renewable energies in India was 46.4 GW in 2016 which wind power participated in more than 60% (Jethani, 2016). However, China is the pioneer Asian country in wind technology. Although the golden years of the significant annual increase in the market are probably passed away, still China is the global largest market so far. In the last decades, the extraordinary development in wind technologies in China makes the effort of investigation in their policy so interesting. Fig. 9 shows the historical review of various policies that have been implemented by China through wind technology.

As is obvious in the above figure, 26 policies have been applied from 2006 to 2018. One of the policies which make China the pioneer country in both, electricity production and technology development in the wind sector is the provincial policies. Nonetheless, the central government has a remarkable in promoting wind technology in China (Zhang et al., 2016). The amount of electricity production by China through wind technology is 286.1 TWh in 2017 (Company, 2018). The latest policy, according to Fig. 9 is regularity instrument type, which was established by the National Energy Administration (NEA) of China. This policy is regulating technical and non-technical aspects of constructing and developing the onshore wind projects. Among the top ten countries, which have been published patent in wind technology, China is the leading country in electricity production.

India is the other accelerated country in wind power technology. In contrast to China with 7307 patents, the total published patent by India in the wind technology sector is only 180. Nonetheless, India is the second-largest Asian wind electricity generator. Follow India, Japan is the third-largest electricity producer through wind power with 5.7 TWh in 2017 (Company, 2018), while publishing by 6704 patents is the fourth top country. The last but not the least Asian pioneer country in wind technology is South Korea. According to the BP report, the amount of electricity was produced through wind power by South Korea in 2017 was 2.2 TWh (Company, 2018).

The gross additional wind power capacity that has been added by European countries in 2017 was 16.8 GW. This 25% increase in total capacity in comparison with 2016, held as a new record for Europe. Consider all other sources that are being used by Europe countries for power generation, wind power after passing Coal in 2016 become the second largest form of power generation capacity following gas installation (Fig. 10).

In spite of being in the top five technology leaders in wind technology, the Netherlands is not the main electricity producer among European countries. Germany is the leading country in both, technology development and electricity generation in the wind technology sector in Europe. In 2017, Germany added 42% wind installed capacity and the leader of European countries followed by Spain, the United Kingdom, and France (Europe, 2018). Although the highest number of published patents after Germany related to Denmark, the United Kingdom (UK) by producing 49.6 TWh in 2017 is the second top country (Company, 2018). Nevertheless, due to the previous section review on sub-technologies in wind power, identifying the most effective ones in the future this renewable resource would be beneficial. In order to achieve this aim, the domain analysis has been done. In this analysis, the main domain of published patents is investigated. The major parts of wind power technology, as it mentions earlier, are considered as blades and rotors, components or gearbox, control of turbines, generator or configuration and nacelles.

According to Fig. 11, technologies related to blades and rotors and control of turbines have the most published patents in

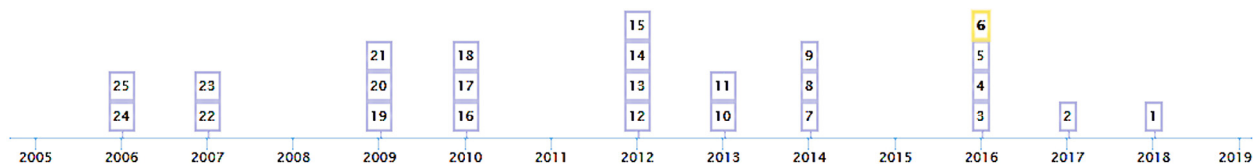


Fig. 9. A brief history of the Chinese policies in the wind power sector (IEA, 2018).

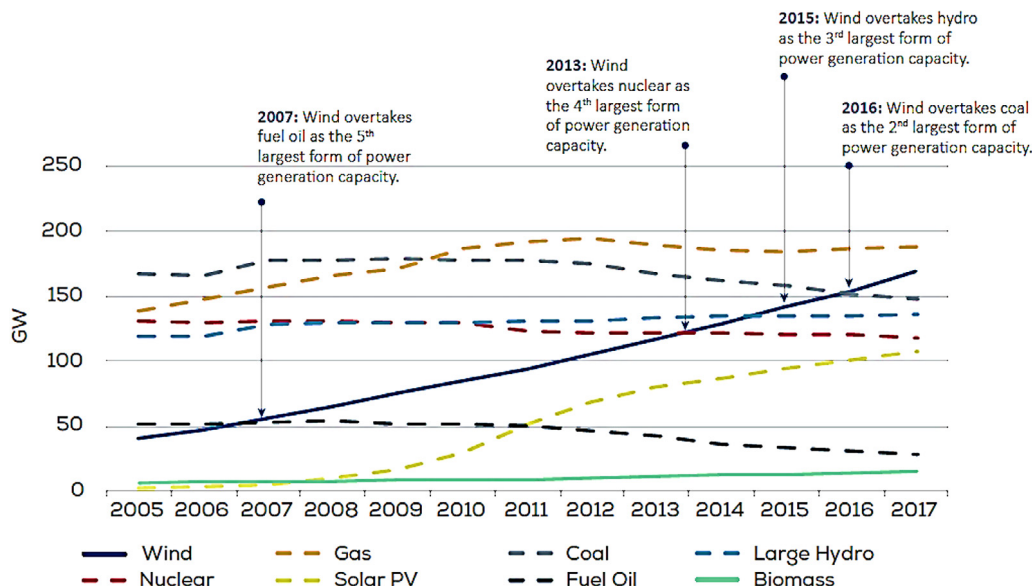


Fig. 10. The history of wind power generation capacity in Europe compared the other sources (Europe, 2018).

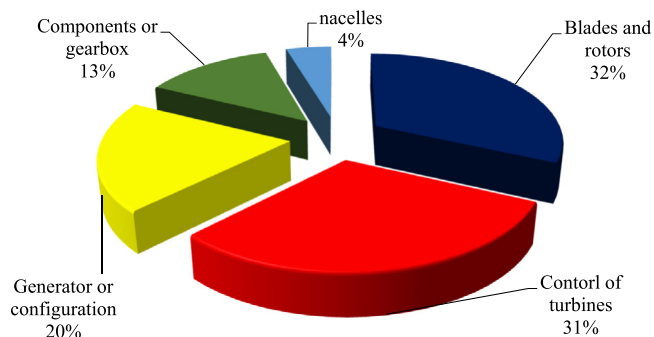


Fig. 11. Published patents in various technological parts of wind power technology.

the wind power technology with 32% and 31% respectively. The technological part that gained less attention between other parts is nacelles with 4% only. It can be concluded from Fig. 11 that the blades and controlling system are the main topics in research and development of the wind power sector. As was discussed earlier, all modification has been made to first enhance the wind turbines performances and secondly and more importantly increase the amount of harvesting energy that captures from the wind. The first challenge can be addressed in all selected domains, nonetheless, the control of turbines play a critical role. To boost the energy harvesting yield, blade and rotors can be considered as the main domain for answering this challenge.

5.1. Text analysis

Clarifying the wind sub-technologies in five main groups requires more detail information for further applications, such

Table 1

The frequent keywords in blades and rotors domains.

Domain	Keywords	Frequency	Domain	Keywords	Frequency
Control of turbines	pitch	3488	Blades and rotor	Blade	12 722
	energy	3353		Turbine	10 891
	hub	1661		Rotor	7 134
	tower	1619		Energy	3 007
	grid	1284		Hub	2 999
	torque	1268		Tower	1 387
	gear	1151		Pitch	1 361
	parameter	1143		Nacelle	1 060
	yaw	1076		Wheel	1 052
	response	831		Fiber	498

as decision-making. For this respect, reading all the published patents individually in the considered domain might be a boring investigation and requires lots of free time. However, analyzing the main keywords in the text and the amount frequency of each one might determine the main idea or the main discussed subjects of that patent. Indeed, the frequency of each keyword can consider as a factor of importance. Therefore, the results of text analysis for each sub-technologies, which are categorized in the previous sections, are discussed in the following. As is obvious the numbers of patents that have been published in the technology of “Blades and rotors” are more than “Control of turbines”. Nonetheless, one of the important parts of wind technology is controlling. In order to make wind turbines more efficient and reliable an advanced control system is required. Table 1 illustrates the most frequent keywords in “Blades and rotor” and “Control of turbines” domains.

Disturbance of the frequent keywords in the extracted patents of “Blades and rotors” shows the frequent keywords that have been repeated a lot in the text of the published patent are “blade” and “rotor” so far. Most of the patents have discussed in the rotor

and blade domains. The cost of wind turbines manufacturing is one of the stimuli for promoting wind technology. The cost of generated electricity is deeply related to the manufacturing expense. It is estimated that about 15%–20% of the total expenditure of manufacturing of turbine is related to the blade (Sood and Tellis, 2005). Due to attain the highest possible energy from wind, the blade requires to be designed in appropriate shapes. The three words “blade”, “rotor” and “hub” are considered a lot in the patents published. What can be concluded from the outputs of text analysis proves the important roles of designing these three parts of wind technology on the total production cost. To harvest a higher speed of the wind, the higher hub-height is required. Increasing the hub-height can result in the profitability of wind power and have political and economic advantages regarding the high amount of power which will be generated. The other factor is swept areas of turbine that belongs to a blade. The larger blade can result in more areas that swept and consequently ameliorate the efficiency. To amortize the cost of developing blades and hub the larger output must be seen, nonetheless the higher hub-height and larger blades besides a huge challenge in designing cost more. As is mentioned, larger blades require strength and appropriate structural design as a load in turbines. Therefore, these three parts of wind turbines; blade, rotor, and hub, regarding their vital role in the cost of manufacturing. Considering the frequent keywords in Table 1, the results of the text analysis of published patents shows the “lightning” is repeated considerably. One of the serious problems caused by natural phenomena for wind turbines is lightning. While the wind turbines are preferred to launch on the hilly terrain, they are at risk of being a victim of lightning (Yamamoto et al., 2009).

The other domain with a high number of published patents is “Control of turbines”. The result of the text analysis of this domain is also shown in Table 1.

According to the results of text analysis, “pitch” is the most repeated word in the text of the patents. In wind technology, the stranger winds can cause damages in the turbines. Therefore, it is so vital to waste excess energy. Various kinds of power control are designed with turbines to address this problem. One of these control methods is pitch control. The pitch controller monitors the output-generated energy from blades several times in a second, when the excess power determined, the pitches of turbines blades turn out of the wind. Controlling the pitch is power regulation and causes lighter blade construction. The other word, which repeated a lot in the text of the patent, is “response”. Fast responding is considered one of the important features of every controller systems. If the paces of response are not adequate, the blade and generally the turbines will be damaged. Therefore increasing the response of controller output can decrease the total damage of turbines. The other hot word is “torque”. The kinetic energy of wind through rotor blades can be converted to torque power. While the speed of wind fluctuates, the torque in the shaft will fluctuate, and consequently, the amount of electricity conducted to the grid will cause a non-appropriate output (Kulka, 2004). However, controlling the torque according to the wind parameters seems critical. One of the important parts of horizontal axis wind turbines is the yaw part. To harvesting the wind energy the rotor should be against the wind pattern, the yaw mechanism role is to ensure that the rotor is pointed to the wind pattern. In order to increase the efficiency and harvest the maximum amount of energy of wind, controlling the yaw is a vital requirement. The other word that has been considered a lot is “yaw”. Regarding the important roles of yaw in optimizing the total cost of designing, it is not surprising that the R&Ds have made efforts in this domain. It is noteworthy to say; it can be grouped the top repeated words in the patent text in two main sectors; electrical issues and mechanical issues. While the words like “pitch”, “torque”,

Table 2
Frequent keywords in other wind technology domains.

Domain	Keyword	Frequency
Generator or configuration	stator	2959
	tower	1367
	grid	1178
	battery	1163
	gear	1028
	fan	913
	hub	827
	pole	744
	cable	479
	sea	396
Components or gearbox	gear	1922
	oil	579
	gearbox	573
	roller	564
	lubrication	482
	bolt	459
	flange	459
	cabin	458
	safety	332
	stator	260
Nacelles	hub	682
	crane	205
	gear	196
	stator	162
	torque	138
	lightning	136
	foundation	132
	platform	128
	flange	127
	beam	65

“yaw”, “wake” and “velocity” are identified the mechanical issues of wind technology, the other words such as “network”, “grid”, “noise” and “response” are indicating the electrical issues. In fact, both domains of technology, mechanical and electrical, are considered to control wind power. Investigating patents text that has repeated “farm” word demonstrates that the main concern in the wind farm system is managing. In order to clarify more about each domain frequent keywords, the entire extracted keywords are shown in Table 2.

All of the five domains top ten frequent keywords are illustrated in the above tables. Two main issues in wind technology have a critical impact on wind technology development. First, one is a capital investment. The turbines expenditure is the highest cost of wind technology. The high operation and maintenance cost is the other challenge in harvesting wind power. Regarding this challenge, appropriate monitoring that is enhanced by an applicable and reliable control system can reduce the operation and maintenance cost (Foster, 1988). According to the challenges that have been discussed, the most frequent keywords are addressed the main issues. For enhancing the efficiency of wind turbines the height of the tower and the radius of the blade are the keywords that are considered for these challenges in the patents. In the literature review, the importance of WECS has been reviewed and the critical role of pitch control in WECS is indicated. The high frequency of “pitch” in control of turbines domain demonstrates this fact.

5.2. Technological life cycle analysis

The other question that should be answered is the technology status of each domain. The exact position of technology in the development curve would be helpful for policymakers. The technological life cycle of each wind technology domain has been curved, and the future of each one has been forecasted. For a better insight into the various domains, their technology trend is illustrated in Fig. 12.

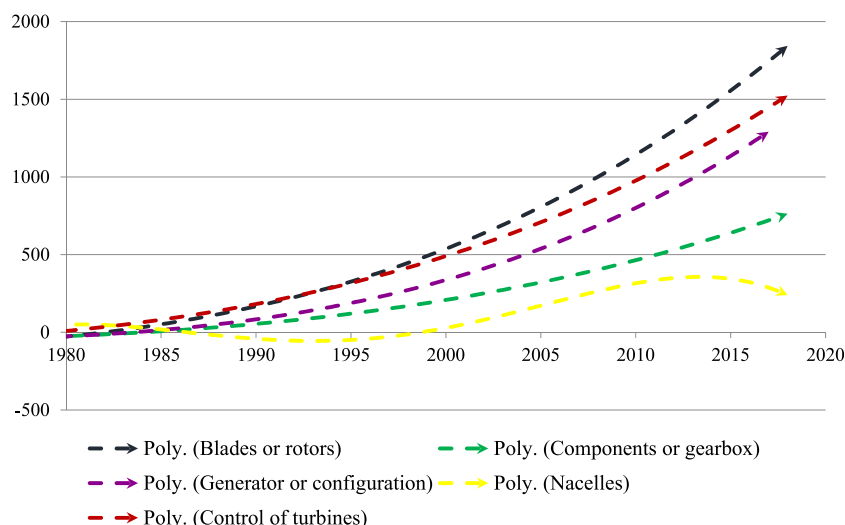


Fig. 12. The trends of technology domains in wind energy.

As discussed earlier, the blades and rotor are important factors of wind technology development, the upward with a high slope of “Blades or rotor” domains trend, according to Fig. 13, proves this fact. The next highlighted domain is “Control of turbines”. The trend of this technology shows that still, this domain is the main issue in developing wind technology. In spite of other domains which are upward albeit, in various rate, the only technology which has been neglected recently is “Nacelles” domain. The next question which will be answered is the determination of these domains future visions. In order to find out the future of these domains in wind power technology, technological life cycles of each domain are curved below.

The technological life cycle of “Blade or rotor” domain is illustrated in Fig. 13. According to this curve, it can be concluded this domain of technology locates in the growth stage. Investigations in proper materials for designing the blades are ongoing. The other influential factor for improving the blade is the size of it. In fact, wind technology development is twisted in increasing the blade size. As discussed earlier, the production cost of wind turbines is a vital option for technology development. The leveraged cost of energy can be reduced by increasing the size of the blades. As a matter of fact, while the size of blades increases, the area which has been swept by the blades will be extended, ultimately, the amount of harvested energy will be increased. A comprehensive study has been done by the Department of Energy (DOE), National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) through the WindPACT program (Ashwill, 2004). In this program, the limitation and constraints regarding wind turbine scaling (Ashwill, 2004). According to this program, one of the barriers to increase blade size is transportation. While the size and height of blades increase, the transport of blades becomes a serious issue. The oscillating load due to size growth is the other limitation. While the size of the blades grows, the gravity becomes an issue. The lighter blades are required by using materials with high strength and lightweight.

The technological life cycle of “Control of turbines” domain is illustrated in Fig. 14. The growth stage is the current phase of the “Control of turbines” technology domain. It is discussed that the main factor of developing and promoting wind technology is the reduction of produced electricity cost. Optimization, the performance of the wind turbine, can result in high electricity production and advanced controlling is one of the levers. One of the barriers of current wind technology is related to controlling turbines which have been under the excessive loading in

the turbulent condition. Improving the current advanced pitch control can be helpful. This technology domain is in the growth phase, nonetheless passed the productivity point (50% of growth per time) and the next generation or approach is required to enter into the maturity phase. The next technology domain is “generator or configuration”. A generator of wind turbine plays a critical role when encounter to a turbulence wind with a fluctuated speed. The main barrier in this technology is to confront the fluctuating nature of wind power. The result of the technological life cycle, regarding Fig. 15, demonstrates that this technology domain is in the growth stage. The R&D efforts should be made to enter into the mature stage. The only domain of wind technology which is still in the emerging phase is “Components or gearbox”, according to the Fig. 16. While the gearbox is on the expensive component of wind turbines, repair its failure will cost a lot and subsequently increase the produced electricity cost (Feng et al., 2013). In fact, an uncertain life expectancy of the gearbox forces the manufactures to add large contingencies to the failure and consequent damage that will become intense the wind turbine price. Due to reducing cost larger turbine should be launched; therefore the accessibility to gearbox becomes a major challenge. Emerging the next generation through R&D efforts are needed to ameliorate long-term gearbox reliability (Musial et al., 2007). According to Fig. 17, the only technology domain that reached the maturity stage is “Nacelle”. The generator and related rotating equipment are placed in the nacelle; therefore the nacelle is heavier than the rotor, and the diameter of the rotor and the strength of it is mostly depending on the weight of the nacelle (Islam et al., 2014). One of the devices in the nacelles, which is so heavy and large, is the step-up transformer. Elimination of this transformer can reduce the weight of the nacelles and results in lower-cost production significantly. Recently, the high pace development of semiconductors which got to their mature status can solve the weight issue of step-up transformers (Islam et al., 2014). The improvement of medium voltage converter and the high-temperature superconductor (HTS)-based generator may cause a huge economic saving in construction and installation. The current R&D efforts have been brought these technologies in the maturity phase, but still, improvement and development are required. The result of forecasting of wind technology domains and their current status are represented in Fig. 18.

The current status of each main technology domains is shown in Fig. 18. The three of mentioned domains; “Generator or configuration”, “Blades and rotor” and “Control of turbines” are in

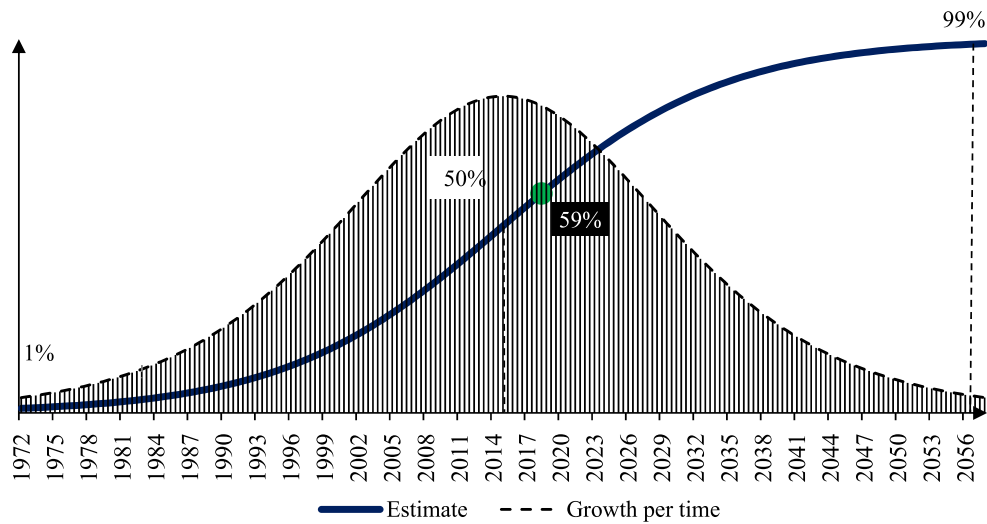


Fig. 13. The technological life cycle of "Blades and rotor" domain.

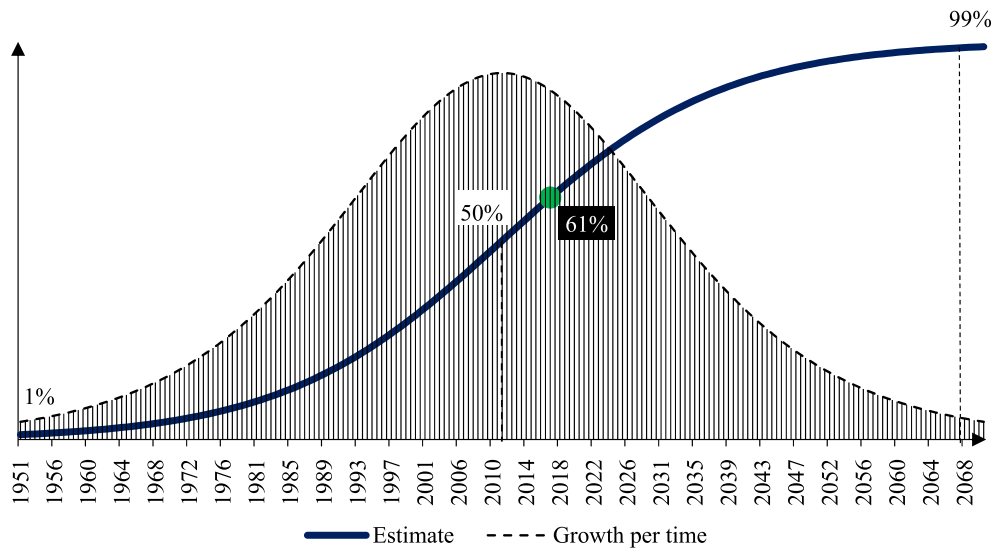


Fig. 14. The technological life cycle of "Control of turbines" domain.

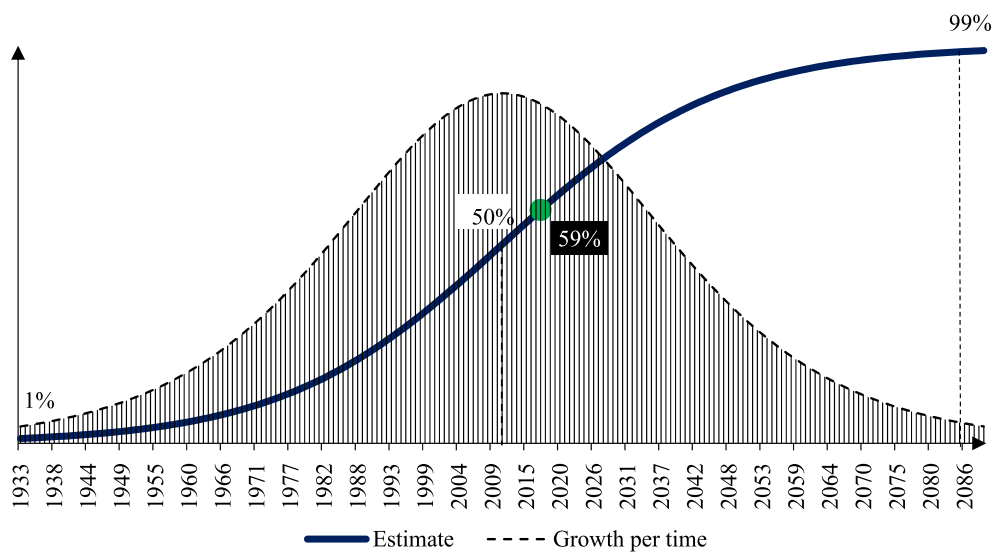


Fig. 15. The technological life cycle of "Generator or configuration" domain.

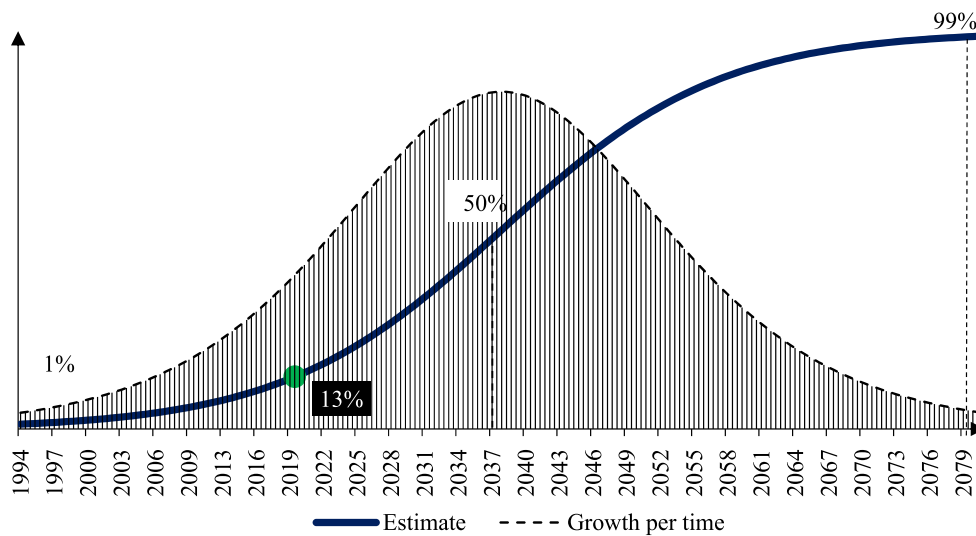


Fig. 16. The technological life cycle of “Components or gearbox” domain.

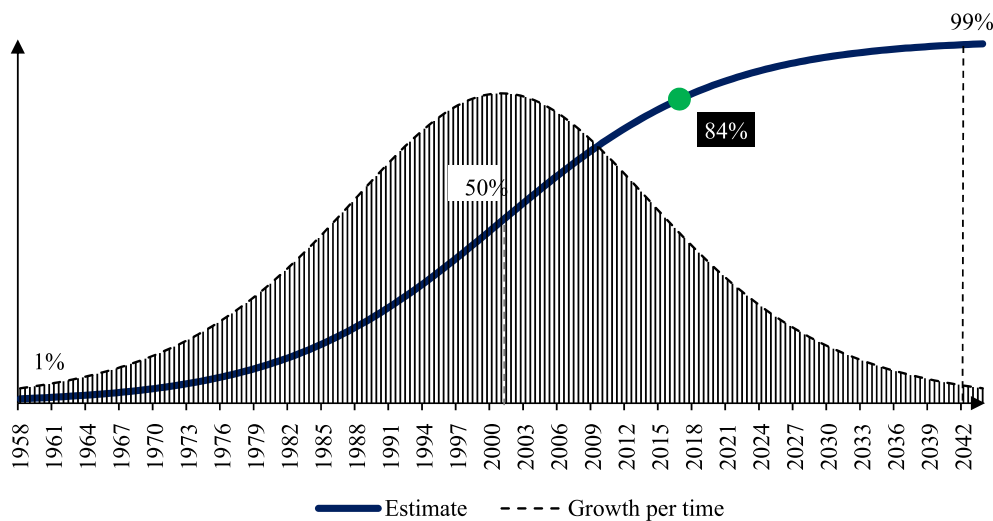


Fig. 17. The technological life cycle of “Nacelle” domain.

the growth stages. The next generation of these technologies is needed to move to the maturity phase. Larger blades are required to meet the affordable energy supply for the expected energy crisis. Control of turbines is the other participated in a growth stage which is near to enter into the maturity phase. The main issue in this technology domain is controlling the blades in the turbulent conditions. While the nature of the wind profile is to fluctuate, optimize the performance of the wind in the turbulent conditions can result in cost reduction. It can be expected the next generation or development of current “Control of turbines” technology domains will work on optimization of wind performance in the turbulent situation. According to Fig. 15, it can be predicted that the “Generator or configuration” technology domain will face the maturity phase in 2040. The only technology domain that located in the maturity phase is “Nacelle”. Still, development is required to reduce the weight of nacelles. Improvement of the semiconductor to eliminate the step-up transformer in order to enhance the weight challenge will be the next step in this technology domain. While the life expectancy of gearboxes is so uncertain and on the other hand, their accessibility is so poor, regarding the position of a gearbox, enormous R&D efforts should be made to resolve this issue. This technology domain is in the emerging stage and will enter into the growth phase in 2030.

6. Conclusion

We discussed wind energy sub-technologies and determined their technological states. Five domains of technology have been introduced for developing the wind industry that is “Generator or configuration”, “Blades and rotor”, “Control of turbines”, “Component and gearbox” and “Nacelle”. The results demonstrated that “Blades and rotor” and “Control of turbines” are two main technology domains which have been gained lots of attention by pioneer countries in wind power and has participated in more than 32% and 31% published patent respectively. In order to determine the main issues in each domain, the text analysis has been done. The results of text analysis indicated the main issue in controlling wind turbines is pitch control and the main challenges in blades and rotor domain is designing. The results of the text analysis of each domain illustrate. Eventually, trend analyses of each domain, besides technological life cycle have been discussed. It is found that the component and gearbox domain is in the emerging stage while the nacelle technology domain passed the growth phase in 2015.

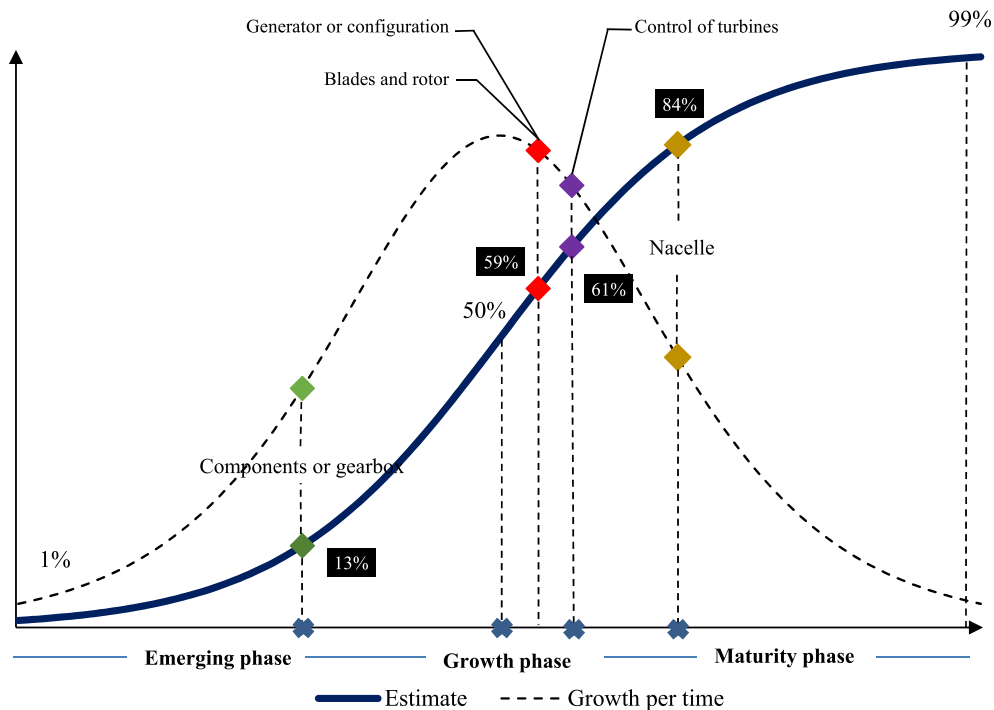


Fig. 18. The current status of technology domains in wind technology.

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