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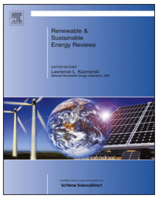

Wind energy generation technological paradigm diffusion

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ABSTRACT

This paper investigates the role of the technological paradigm for the development of wind energy technology, and aims to contribute towards recommendations on technology policy and management. The paradigmatic research was conducted using a novel data analysis system (DAS) and a wind energy generation technological diffusion mathematical model. The wind energy generation technological paradigm (WEGTP) composed of paradigm competition, diffusion and shift was established to explain the technological changes in the use of wind energy. Simulation results show that the development of installed capacity for wind energy generation has a strong inertia force along with the S-curve. Global annual installed wind capacity reached a peak in 2012 and is estimated to be saturated by 2030. Hybrid wind and solar energy generation technology appeared to be more promising than wind energy technologies that rely only on onshore or offshore winds. To further accelerate wind energy development, specific subsidies and incentives need to be provided in areas such as capital costs and technological support.

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1. Introduction

In the New Policies Scenario, global energy demand is expected to increase by one-third from 2011 to 2035, and electricity demand is expected to grow by more than any other final energy form [1]. Energy generation related CO_2 emissions play a significant role in environmental degradation. The application of renewable energy technologies has been selected as useful technical and policy-based choices that ensure a certain extent of environmental sustainability. Compared with fossil energies, renewable energy sources, such as wind, solar, and biomass, have abundant long run raw materials. As the global economy continues to grow through the twenty-first century, it is well known that there is enough power in the earth's winds for wind to be the primary source of near-zero-emissions electric power.

Wind energy has seen an impressive development over the last two decades, from only 3.5 GW in 1994 to around 320 GW of cumulative global capacity at the end of 2013. In the New Policies Scenario, electricity generation from wind (onshore and offshore) is projected to increase at an annual average rate of 6% between 2011 and 2035, and governments could act to significantly reduce the cost of wind power and increase its energy contribution share of global power supply from its current 2.6% to 18% by 2050 according to the International Energy Agency (IEA) Roadmap [1]. China, the European Union and the United States expect to see the largest increases in wind electricity and it is expected that by 2035 around 70% of the world's wind power generation capacity will be in these three regions. Wind energy now accounts for one-third of total investment in renewable capacity, followed by hydropower (27%) and solar PV (23%) [2]. According to one study, the production cost of wind turbines, and consequently the power production costs, can decline by as much as 15% when cumulative volumes double [3]. Another statistical analysis has claimed that the cost of producing one kilowatt hour (kWh) of electricity has decreased to 20% of the initial cost [4].

Many studies have examined wind energy generation. The use of wind energy goes back nearly 3000 years, and was originally used to propel ships, drive windmills to grind grain and to pump water. After the two oil crises in 1973 and 1979, wind power's traditional uses were expanded to encompass electricity production. An overview of the wind energy technological development path indicated that wind turbine technology has now reached a reliable and sophisticated level [5,6], with offshore wind farm technologies having been developed [7,8] and studied in China [9], Europe and North America [10]. As wind is seen to be somewhat unreliable, offshore wind energy generation technology needed development breakthroughs, so hybrid renewable energy system (HRES) methodologies and models were investigated and described in [11–13]. Many scholars have expressed concern regarding the wind energy generation technological diffusion problem. Given the potential of renewable energy technologies for sustainable development, different diffusion theory based models and their applicability to renewable energy technologies diffusion analysis have been proposed [14,15], such as the diffusion of wind energy in Japan using an interaction between the technology and the markets [16]. Further, a focused study concluded that clear and focused energy policies can assist in increasing wind energy technological diffusion [17,18].

There has been thousands of research papers focused on wind energy generation. However, due to the lack of a systematic analytical framework, much of this research has little integrity or universality. When seeking to describe technological change and innovative research, the technological paradigm provides a sound method for the investigation of past trends as well as being able to predict future possibilities. This article adopts a technological paradigm to determine a wind energy technologies road map which could pave the way to the expansion of supply and an increase in efficiency.

The term paradigm first appeared as part of Kuhn's theoretical contemplation on the historical development of science [19]. Dosi applied the paradigm to technological innovation and proposed the technological paradigm concept, which still has substantial underexploited analytical potential [20–23]. The technological paradigm is mainly applied to analyze technological change and innovation in engineering fields [24]. By combining the technological paradigm concept with the wind energy generation technological diffusion process, in this paper, a wind energy generation technological paradigm (WEGTP) is proposed which aims to contribute recommendations for technology policies and the consequent management. The WEGTP was established using two procedures. The first, which was used to determine the keyword trends from a qualitative perspective, was a data analysis system (DAS) made up of the Web of Science database (WoS), NoteExpress and NodeXL. The WoS was chosen as the primary database to search for relevant wind energy utilization literature, NoteExpress was applied to review the general characteristics by reading the papers' titles, abstracts and keywords, and NodeXL was used to analyze the selected articles' bibliographies. Therefore, the DAS, as a comprehensive integrated approach, was able to guide our research in the potential WEGTP development direction. Compared with more simplistic statistical tools, this method was able to elaborate the mutual relationships between the keywords and time. The second method was a mathematical model based on physics field theory, which was used to simulate and forecast the installed wind energy generation capacity from a quantitative perspective. The WEGTP illustrates wind energy's technological utilization evolution from a qualitative and quantitative perspective, which, to the best of our knowledge, is a new research area.

The rest of this article is organized as follows. Section 2 discusses the Data Analysis System (DAS), which identified and summarized the main technological trajectories and uncovered wind energy field development trends. The wind energy technological diffusion mathematical model and three stages of WEGTP are presented in Section 3. Section 4 puts forward the wind energy generation evaluation and some constructive suggestions about how to promote wind energy technological diffusion. Conclusions and recommendations for future research are provided in Section 5.

2. Literature mining

Wind energy has an extensive and wide ranging history. However, the quantity of research in this field makes it difficult to determine the knowledge gaps or to explore future research possibilities. Literature mining is a powerful method for elucidating major trends across time in published scientific literature and allows for topic maps to be built [25]. Garfield believed that the citation indexing of academic literature was crucial for researching similar research topics [26]. A citation index is a synthesized result based on journal articles, keywords, publication dates and abstracts and is able to demonstrate the influences in a specific field. Moreover, research which has the greatest impact in a specific field can be easily identified using a citation index. In this way, current developments, technologies, trends and potential fields of research emerge. In this section, the development of the DAS and the research process are described and the visualization results presented.

2.1. The data analysis system

Literature review metrics have been used in supply chain analyses to increase performance and overcome the barriers to renewable energy supply chain development [27]. Bibliometric analysis of citations to Dosi has also guided the development of technological paradigms [23]. In order to focus on wind energy utilization keywords trends, a data analysis system was created based on Scientometrics [28]. To discover the wind energy utilization keywords trends, the DAS provides a comprehensive meta-synthesis approach through the use of the ISI Web of Science database (WoS), NoteExpress and NodeXL. WoS was chosen as the primary database, as it gives access to multiple databases that reference cross-disciplinary research, and therefore allows for an in-depth exploration of the specialized sub-fields within an academic or scientific discipline. NoteExpress was applied to review the general characteristics, as it can efficiently and automatically search, download and manage research papers in a variety of ways. NodeXL was used to analyze the bibliographies, as it is a powerful and easy-to-use interactive network visualization that leverages the widely available Microsoft Excel application to generate generic graphical data, perform advanced network analysis, and provides a visual exploration of the networks [29]. Therefore, the DAS, as a comprehensive integrated approach, guided our research towards the potential WEGTP development direction, as shown in Fig. 1.

Since the ISI Web of Science is rich with knowledge, it is difficult to select useful articles if the appropriate searching strategies are not specified. To ensure no important documents are overlooked or duplicated, the appropriate methodology in this article is in accordance with the following rules.

(1) In order to guarantee search efficiency, there needs to search wind utilization using keywords, such as development, transformation, conversion, application and trends in the scope of article's "topical subject", rather than looking at the full range.
(2) Duplicate checking work was conducted to remove unnecessary or irrelevance research through a reading of the titles and abstracts in NoteExpress.
(3) In NodeXL, research themes are more concentrated by combing and merging the similar keywords, e.g. a wind turbine is similar to wind turbines.

The considerable number of total papers reveals the considerable attention devoted to wind energy in the last years. Based on these rules above, the 9463 initial wind energy application records were reduced to 796 articles. After thoroughly and carefully removing duplicates in NoteExpress, the final analysis was 296 articles which were representative of wind energy utilization. Keywords from these articles were grouped by publication year using NodeXL, with the final grouping of articles ranging from 1994 to 2014. Therefore, 'year' and 'keyword' as the two vertexes formed an edge and the keyword focus trends were shown on the horizontal axis.

2.2. Keyword focus trend analysis and results

According to the DAS, the current research is reviewed, from which we were able to identify and summarize the main technological trajectories of wind energy technologies in the last twenty years. Differing from frequency analysis, the network developed in NodeXL shows an interaction between 'publication year' and 'keyword'. After calculation and rearrangement in NodeXL, the primary analysis results being determined as shown in Fig. 2.

From the above figure, the keywords foci show a trend in each phase with each yearly increment. Below the year vertexes, there are several keywords such as 'wind power generation', 'offshore wind power', and 'hybrid energy system', which were the main topics of this research. Therefore, these keywords became the focus for all years from 1994 to 2014, as more clearly shown in Fig. 3.

From 1994 to 2000, the main keywords 'windmill', 'power regulation', 'electricity' and 'wind turbine' were the main research foci because the connecting lines between the 'year' and the 'keyword' are primarily concentrated in these years. From 2001 to 2009, keywords such as 'offshore wind farm', 'offshore wind turbine', 'offshore wind generation system', 'HVAC', 'HVDC', and 'tower support' were the main research foci. Keywords such as 'complementary power generation', 'wind PV system', 'wind solar hybrid system', and 'wind diesel system' were the main research foci for the more recent years from 2010 to 2014. From this analysis, we were able to predict the future wind energy technological development trends to be complementary or combined wind and other energy sources, such as wind and hydro power generation systems, wind/diesel hybrid power systems, wind and biomass power generation systems, and, in particular, wind solar hybrid power systems.

The above analysis showed that the wind energy research foci were generally divided into three stages. Onshore wind energy generation technology was the main technology in the first stage, which included sail wind generators, water pumping windmills, and wind heating. Offshore wind energy technology was the main wind energy technology in the second stage, and in the final stage,

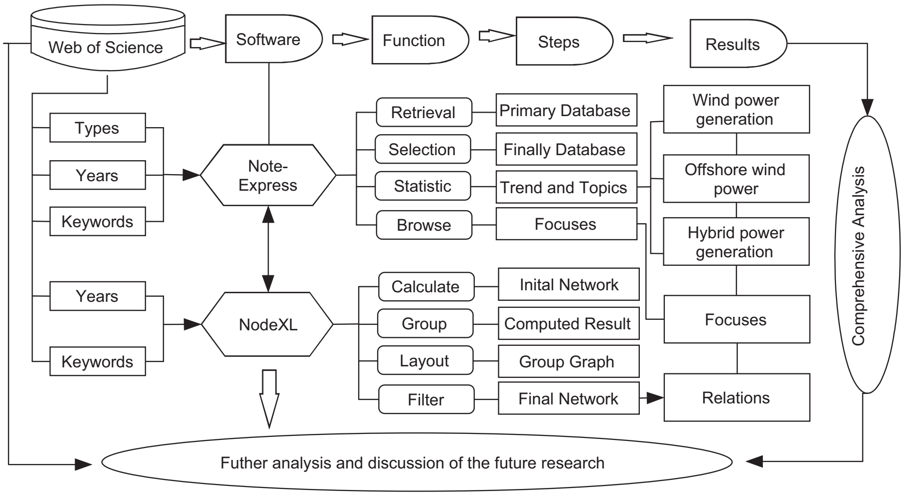

Fig. 1. Research documentation meta-synthesis method.

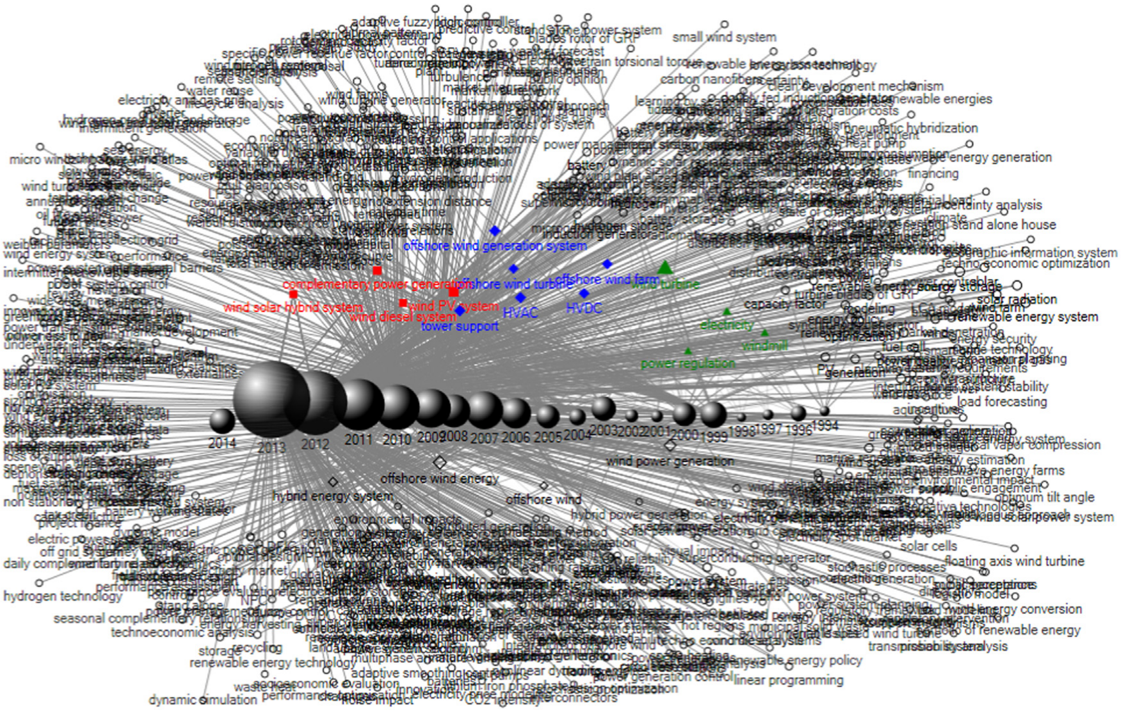

Fig. 2. Keywords focus trend analysis graph.

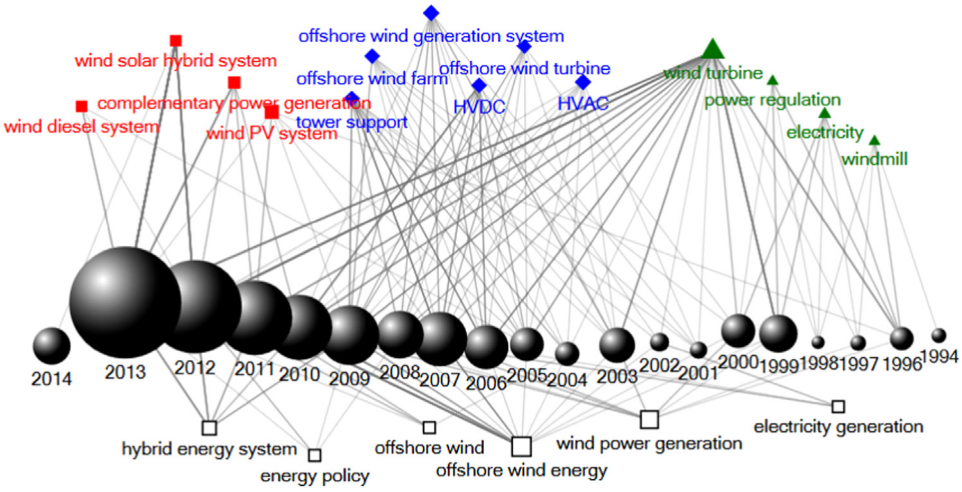

Fig. 3. Wind energy utilization keyword focus trends.

the future potential wind energy technology was directed to hybrid wind and solar energy generation technologies. By combining the technological paradigm with the wind energy generation technologies diffusion model, a novel concept for the wind energy generation technological paradigm (WEGTP) was able to be proposed.

3. Wind energy generation technological diffusion model and WEGTP

In this paper, a technical paradigm was introduced to explain how the technology involved changed in a valid search direction and what was considered a technological improvement. A paradigm is therefore a collectively shared logic as to the convergence of a technological potential, the relative costs, market acceptance, functional coherence and other factors [30]. The technical paradigm is also a model which attempts to account for both continuous changes and discontinuous changes in technological innovation. Continuous changes are related to the progress along the technological trajectory defined by a technological paradigm, while discontinuous changes are associated with the emergence of a new technology. The continuous technological paradigm goes through a complete life cycle, from birth, growth, maturity to obsolescence. Three phases were distinguished to describe technological evolution [31]: competition phase, which is characterized by a selection of technical solutions; diffusion phase, which features the industrial learning of the new technical solutions; and the shift stage, in which the emerging market demand for the technology becomes saturated, or unsolved problems appear. The crisis for the technology that appears in the shift stage is then surmounted during a short, non-cumulative period as a new paradigm. The new paradigm, as such, provides a radically different view of reality. In essence, it is not comparable to the previous paradigm, as a rational criteria for their comparison does not exist [32].

3.1. Wind energy generation technological paradigm diffusion model

The acceptance and spread of new technology in a market or user community is commonly referred to as diffusion. This has been an important area of research in several disciplines, such as marketing, strategy, organizational behavior, economics, and the history of technology. The classical diffusion model in marketing literature is the S-shaped curved model of spreading innovations. The typical application of the diffusion S-shaped curve is to new technologies or product categories opening up a new market potential, but not to the competition between an established and a new technology [33]. Here, we examine how a newly available technology diffuses in competition with an established technology.

Technological diffusion can be defined as a mechanism that spreads successful products and technology throughout an economic structure and partly or wholly displaces the existing inferior varieties. The existing research on new technological diffusion is vast, and spills over many conventional disciplinary boundaries. Geroski [34] surveyed the literature by focusing on alternative explanations for the dominant stylized fact that the usage of new technologies over time typically follows an S-shaped curve. There has been several notable diffusion modeling approach reviews [35–39]. A review of renewable energy technological diffusion models is shown in Table 1.

The application of a selected model to the study of wind energy generation technological diffusion emanates from the theoretical basis which states that diffusion processes follow different S-shaped curves. However, the diffusion model parameters needed to be adapted to reflect wind energy market potential, the policy drivers and the technological improvements. Thus, policy makers could use diffusion models to assess the impact of their policies as well as to determine direction to inform the design of new renewable

Wind energy technology diffusion characteristics and existing studies were used to develop the logistics model below which describes the diffusion changes in utilization technologies. The rate and direction of technical change, or the technological choice process, was decided on as result of the competition between fully developed and emerging technological systems. A logistics model based on field theory, which was originally derived from a physics concept, is introduced.

$$\frac{dV(t)}{dt} = rV\left(1 - \frac{V}{V_{\max}}\right) \tag{1}$$

where $\frac{dV(t)}{dt}$ refers to the variation in the wind energy technologies occupancy volume in the market at time t, V is the wind energy project cumulative installed capacity in the country at time t, $V_{\max}$ represents the wind energy technology estimated maximum utilization potential in the country, and $r$is the natural diffusion rate for the wind energy technologies. If we denote$\alpha = \frac{r}{V_{\max}}$, Eq. (1) can also be written as follows:

$$V = \frac{V_{\max}}{1 + Ce^{-\alpha t}} \tag{2}$$

where, C is a constant coefficient and $\alpha$is the self-diffusion rate, which indicates the possibility of employing new technologies. The value $\alpha$was estimated using past data on wind energy technological diffusion.

After taking the derivative of Eq. (2), the wind generation diffusion model is set as in Eq. (3), which is then used to simulate the installed capacity and show the diffusion velocity changes in the technologies.

$$v(t) = \frac{dV}{dt} = \frac{CV_{\max}\alpha e^{-\alpha t}}{(1 + Ce^{-\alpha t})^2} \tag{3}$$

Diffusion modeling is a useful tool for understanding the growth of products or technologies [55]. Although, the diffusion of technologies or products does not follow a single uniform pattern and is a complex phenomenon, models have been used to explain diffusion rates and to estimate the parameters or coefficients for the diffusion model equations. The application of diffusion models has been mainly limited to commercial products with few or no linkages to government policies. The challenge now is to improve experience in applying diffusion models to analyze the WEGTP.

Table 1
A review of renewable energy technologies diffusion models.

Author and year	Model equation	Type of RET/country
Neij (1997) [40]	Use of experience curves $C_{CUM} = C_0 CUM^a$	To analyze the prospects for diffusion and adoption of renewable energy technology.
Isoard and Soria (2001) [41]	Learning curve	Econometric estimation of learning curve was performed on solar PV and wind.
Peter et al. (2002) [42]	Rogers Model	Marketing solar PV technology in developing countries.
Ibenholt (2002) [43]	A formulation for a learning curve taken from Berndt	Compares the utilization of wind energy in three countries Denmark, Germany and the United Kingdom.
Masini and Frankl (2003) [44]	Learning approach	Solar PV systems in southern Europe.
Purohit and Kandpal (2005) [45]	Bass model/Gompertz model/Logistic model/ Pearl model	Future dissemination of RET based irrigation water pumping in India.
Lund (2006) [46]	Epidemic diffusion model (Internal influence model)	Market penetration rates of new energy technologies.
Collantes (2007) [47]	Technological substitution model/Logistic approach	To study the growth rate of fuel cell vehicles market share.
Lund(2007) [48]	Learning by doing (experience curve)	Upfront resource requirements for new renewable technologies large-scale exploitation schemes.
Rao and Kishore (2009) [49]	The Bass model/mixed influence model	Diffusion of wind in different Indian states by linking it to a policy index.
Guidolinand Mortarino(2010) [50]	Bass model/Generalized Bass model(GBM)	Analysis and forecast of the national adoption patterns for photovoltaic installed capacity.
Dalla Valle and Furlan(2011) [51]	Generalized Bass Model (GBM)	Estimates and short-term forecasts for wind energy life-cycles in the US and Europe.
Harijan et al. (2011) [52]	Logistic model	Market penetration forecasts for wind energy in Pakistan under different policy scenarios.
Davies and Diaz Rainey(2011) [53]	Bass model/Davies type B (logistic) models	Tested the international diffusion of wind energy in 25 OECD countries using data sets from BTM and the IEA.
Huh and Lee (2014) [54]	HPKZ (Hahn, Park, Krishnamurthi, and Zoltners) model	Forecast the growth pattern of five RETs: solar photovoltaic, wind energy, fuel cell, solar thermal and geothermal energy in South Korea

[a] is the experience index.

3.1.1. Data set

How wind energy generation is diffused was discussed in detail by combining case studies. In this model, the installed wind energy generation capacity was the independent variable, and referred to the intended sustained technical full-load output of a facility such as a wind energy plant. The diffusion velocity $V$was the annual added installation. We built our analysis on data provided in the Statistical Review of World Energy 2013 [56], for the period 1995–2012.The basic data for wind energy generation annual installed capacity are presented in Table 2.

First of all, the original values for $V_{\max}$ and Cwere assigned. The value of $V_{\max}$ in the mathematical model referred to the saturated wind generation installed capacity in the market, which corresponded to the first year of basic data in 1995 (i.e. $V_{\max}=$ 4778 MW). Then we used the nonlinear regression function in the Statistical Package for Social Science (SPSS) 19.0 to estimate parameters α.

The brevity of these data series could introduce difficulties and uncertainties in the forecasting as there has only been a substantial growth in the wind energy market since the early 1990s. Though a limited number of observations may represent an obstacle, the current growth in the wind energy sector calls for a specific effort aimed at describing and forecasting the market evolution were argued.

Table 2
Wind energy generation capacity worldwide.

Year	t	Annual added installed capacity v (MW)	Total added installed capacity V (MW)
1995	0	–	4778
1996	1	1292	6070
1997	2	1574	7644
1998	3	2338	9982
1999	4	3487	13469
2000	5	4465	17934
2001	6	6901	24835
2002	7	7031	31866
2003	8	8012	39878
2004	9	8057	47935
2005	10	11251	59186
2006	11	14903	74089
2007	12	20002	94091
2008	13	27792	121883
2009	14	38265	160148
2010	15	37725	197873
2011	16	41252	239125
2012	17	45112	284237

3.1.2. Results analysis

C estimation outcome was 247.594, while $V_{\max}$ was 538196.278, and the coefficients $\alpha$was calculated as 0.336. Thus, when assuming $t(1995)=1$, the diffusion velocity model could be constructed using Eq. (4).

$$v(t)=\frac{247.594\times 538196.278\times 0.336e^{-0.336t}}{(1+247.594e^{-0.336t})^2} \tag{4}$$

From this equation, the specific predicted values of global annual installed wind capacity are shown in Fig. 4. The wind installed capacity diffusion velocity reached its peak around 2012. By 2020, the diffusion velocity is expected to be less than 1, and by 2030, it is predicted to be nearly zero.

According to the $V(t)=V(t-1)+v(t), \mathrm{PRED}(t)=\mathrm{PRED}(t-1)+$ $\mathrm{Pred}(t)$, the predicted value of global cumulative installed wind capacity are shown in Fig. 5.

Since 1995, global wind power capacity has continued to grow at an annual cumulative rate close to 40%. Over the past decade, the number of installations has roughly doubled every two and a half years. During 2002 alone, close to 9297 MW of new capacity was added to the electricity grid worldwide. By the end of 2002, global wind power installed had reached a level of almost 34,224 MW. Therefore, according to the model, wind turbine installed capacity is predicted as shown in Table 3.

As can be seen from the above table, the technological diffusion speed three-phase model based on field theory precisely describes the wind energy technological diffusion. The well-known S-shaped curve in Fig. 5 reflects the three WEGTP phases. This can be seen to follow technological life cycle theory, which assumes that wind energy utilization technologies experience three phases: a competition phase, where the wind turbine principle is selected as a new technical solution to resolve problems in the old WEGTP; a diffusion phase, the main characteristics of which are the industrial learning of the new era of wind energy; and a shift phase, in which the market is saturated and new electricity generation production technology appears.

3.2. Three stages of the WEGTP

In Dosi's model, the sense of "trajectory" is aligned with "normal science". He pointed out that technological activities guided by a specific paradigm would form a "technological trajectory" [21]. The technological evolution of the power generation industry can be seen as a succession of technological paradigms which determine the starting points and limits of a new technological cycle of marginal innovations which constitute the technological trajectory in the long-term. From the final effect of the change in each stage of the technological paradigm, the evolution

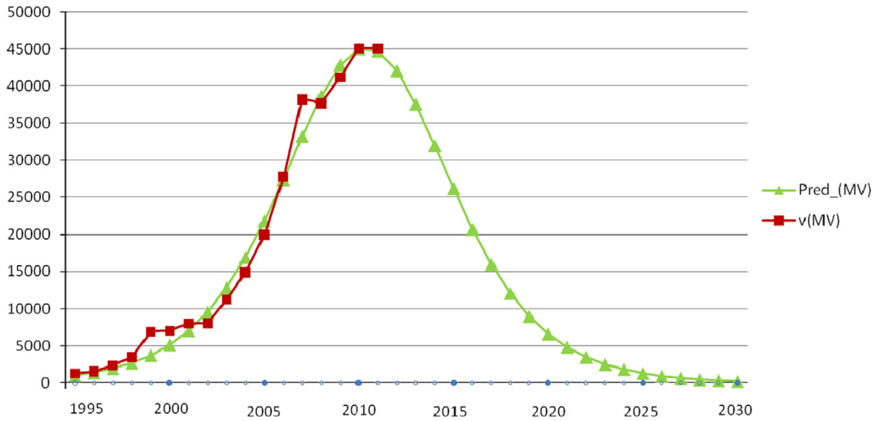

Fig. 4. Predicted value of global annual installed wind capacity.

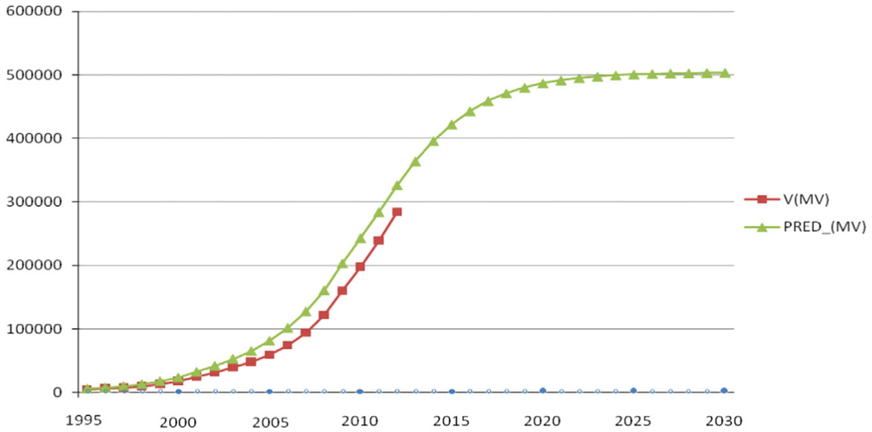

Fig. 5. Predicted value of global cumulative installed wind capacity.

Table 3
Estimated installed capacity (GW), 2013–2050.

	European Union		World	
	Onshore	Offshore	Onshore	Offshore
Installed 2013-2015	34.5	5.5	121	8
Annual installation rate	11	1.8	40	2.7
Cumulative by 2015	135	10	399	13
Installed 2016-2020	48	17	266	31
Annual installation rate	9.6	3.4	53.2	6
Cumulative by 2020	183	27	665	44
Installed 2021-2030	50	85	550	200
Annual installation rate	5	8.5	55	20
Cumulative by 2030	233	112	1215	250
Installed 2031-2050	40	110	725	300
Annual installation rate	2	6	36	15
Cumulative by 2050	273	222	1940	550

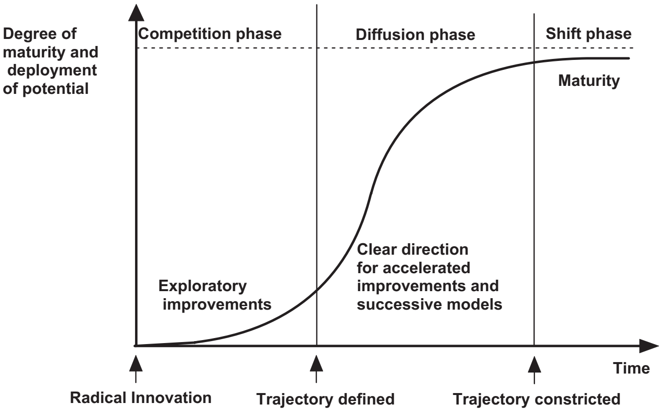

Fig. 6. Three stages of the technological paradigm.

of the technological paradigm can be divided into three stages. The genesis of each technological paradigm follows the trajectory of an S-shaped curve [57], as shown in Fig. 6.

Technical change theories are generally classified into "demand-pull" and "technology-push" theories. Technological competition in the wind energy industry has undergone radical change during the past few decades. With this in mind then, it is important to understand the effects of the push and pull and supply and demand factors on the development of technological paradigms. In the 1970s, when looking at these elements as part of the technological paradigm, it was considered that both were important for innovation and technological development [58]. On the basis of previous studies, the technology-push and demand-pull concepts were defined more specifically by referring to developments in technological knowledge and market changes, both of which are important in determining the course a technological paradigm takes [59].

For the paradigmatic evolution, it is believed that the most important feature of these common technical innovations evolves during the diffusion phase [60]. After fully competing with each other in the preceding phase, the dominant trajectory (or trajectories) inevitably emerges, indicating the gradual movement into the diffusion phase. From an economic view, driven by the interaction of the energy demand in the market and industrial competition, a dominant design emerges in this phase. With the push of the market and the pull of the technology, previous technology is gradually eliminated. Discontinuous changes with the appearance of technology cause the evolution of technological paradigms.

There have been few studies which have specifically examined low-carbon technological paradigms, or, in particular, the wind energy generation technological paradigm (WEGTP). As a result, the progress in this area has been slow with previous achievements partially overlapping and therefore adding little to the area. Thus, there is a need to study the wind energy utilization technological paradigmatic evolution. If the wind energy technological paradigm is established, it could add to the investigation of a reduction in future carbon emissions through the use of renewable energy. Combining the DAS with the S-shaped curve for wind energy technological diffusion, WEGTP could be summarized in three stages, which are characterized by the different technologies: competition, diffusion and shift in Fig. 7.

3.2.1. *Competition phase*

Onshore wind energy generation technology, which includes sail wind generators, water pump windmills, and wind heating systems amongst others, has been the main technology in the competition stage. Wind energy has been utilized for at least 7000 years, and was first recorded as being used for boat navigation on the Nile River in 5000 BCE. Later, vertical-axis mills, which were simple drag devices to provide mechanical power to pump water or to grind grain, appeared. The first details about horizontal-axis windmills can be found in historical documents from Persia, Tibet and China around 1000 CE [61]. These windmills turned wind energy into mechanical energy to help reduce labor needs. As the power market expanded and there was progress in electric power technological development, windmills evolved to the wind turbine which turned mechanical energy into electrical energy. Then a system based on conventional horizontal axis turbines was developed which was a more economical design than using a vertical axis [62]. From then, wind energy generation technology

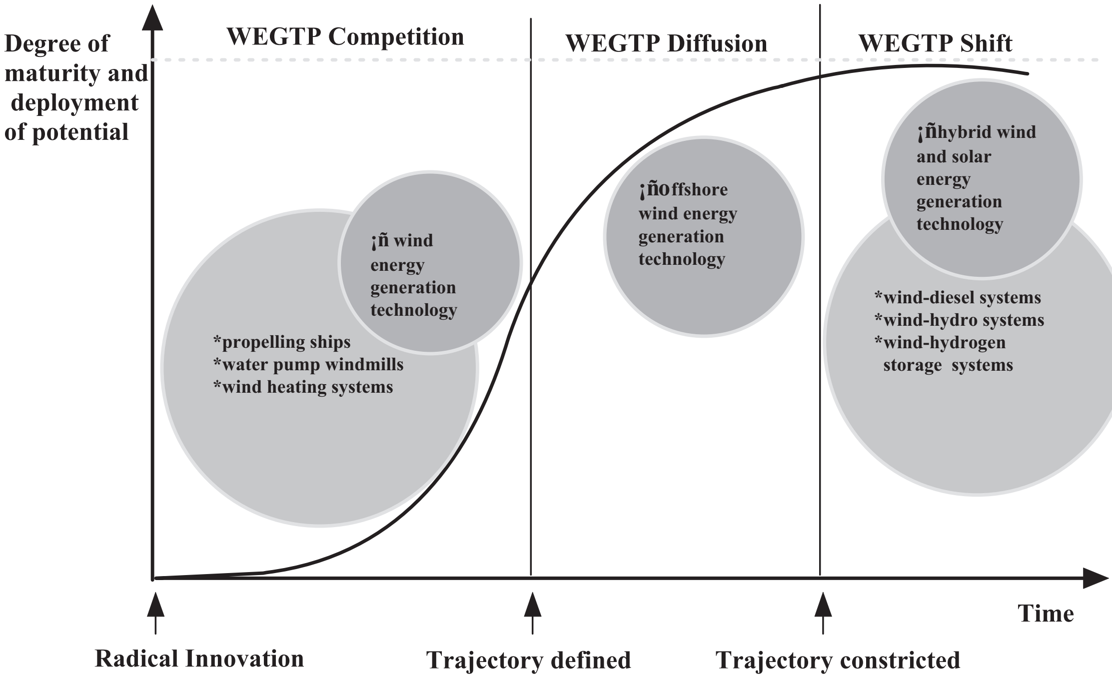

Fig. 7. Technological paradigm for wind energy utilization.

began to be widely used on land. Denmark, which built the world's first wind energy station, was the first country to use the wind for electricity generation [63]. Under market demand and technology pull, wind energy generation gradually became the evolutionary path for the wind energy technological paradigm competition stage. Metz explained that both large and small wind systems have the potential to be competitive with conventional electrical power generation systems [64]. Research has shown that small-scale wind energy systems are suitable in the eastern part of Saudi Arabia for power generation and irrigation purposes [65].

3.2.2. *Diffusion phase*

Offshore wind energy technology was found to be the main wind energy technology in the diffusion stage. The further diffusion of wind energy not only involves a continued expansion on land with the replacement of old plants with new, but also leads to the development of more productive technologies which exploit ocean-based sites [66]. This new possibility may give wind energy a much higher growth potential. There are already test installations in Sweden and Denmark, and there are plans for a further 500 commercial wind power plants producing 2 TW h to be built off the west coast of Sweden. The primary reason that offshore wind energy generation technology is expected to replace onshore wind technology is that the size of onshore turbines is constrained by the available transportation and erection equipment capacity limitations. Transportation and erection problems are mitigated offshore where the size and lifting capacities of marine shipping and handling equipment exceed the installation requirements for multi-megawatt wind turbines. Onshore, particularly in Europe or on the East Coast of the United States, the visual appearance of massive turbines in populated areas may also be undesirable. At a sufficient distance from the coast, visual intrusion is minimized and wind turbines can be larger, thus increasing the overall installed capacity per unit area. Similarly, less attention needs to be devoted to reducing turbine noise emissions offshore, them mitigation of which adds significant costs to onshore wind turbines. Also, the wind tends to blow faster and more uniformly at sea than on land. A higher, steadier wind means less wear on the turbine components and more electricity generated per square meter of swept rotor area. Offshore wind farms are an attractive source of energy because they can be placed in near-proximity to population centers and yet far enough away to mitigate local opposition. However, the cost remains high because of the need to build stable marine structures that can withstand the harsh marine environment for many years without the need for replacement [67].

Conducting research and development into offshore wind energy began in the 1970s and has been mainly concentrated in Europe and the United States. Wang divided this research and development into 5 periods [9]. These are; national research into offshore wind farm resources and technologies in Europe (1977–1988), European-class offshore wind farm research, which began to implement a number of demonstration projects (1990–1998), medium-sized offshore wind farms (1991–1998), the development of large-scale wind farms and large-scale offshore wind turbines (1999–2005) and the implementation of large-scale offshore wind farms (2005-present). The world's first offshore wind farm was built in Denmark, and since then, offshore wind energy has become a new focus in the electricity generation field, as research on wind energy generation also began to gradually transfer from land based systems to ocean based systems. As the development of offshore wind farm technology matures, the 21st century is expected to be the century in which the world's wind energy industry moves from the land to the ocean and becomes an important renewable energy. Offshore wind turbines will become much bigger both in size and power, move further away from the coast and into deeper waters, and the transmission and grid will be upgraded to enable the integration of wind generated electricity. The wind energy technological paradigm then opens to the expansion phase.

3.2.3. *Shift phase*

The shift stage of the WEGTP can be represented by the development of hybrid wind and solar energy generation technology. A feature of wind energy is the unpredictable variability of the strength of the source due to the vagaries of the climate [68]. To solve this instability problem, a more stable power output can be attained through hybrid power systems, such as hybrid wind and hydro energy generation systems, hybrid wind and gas

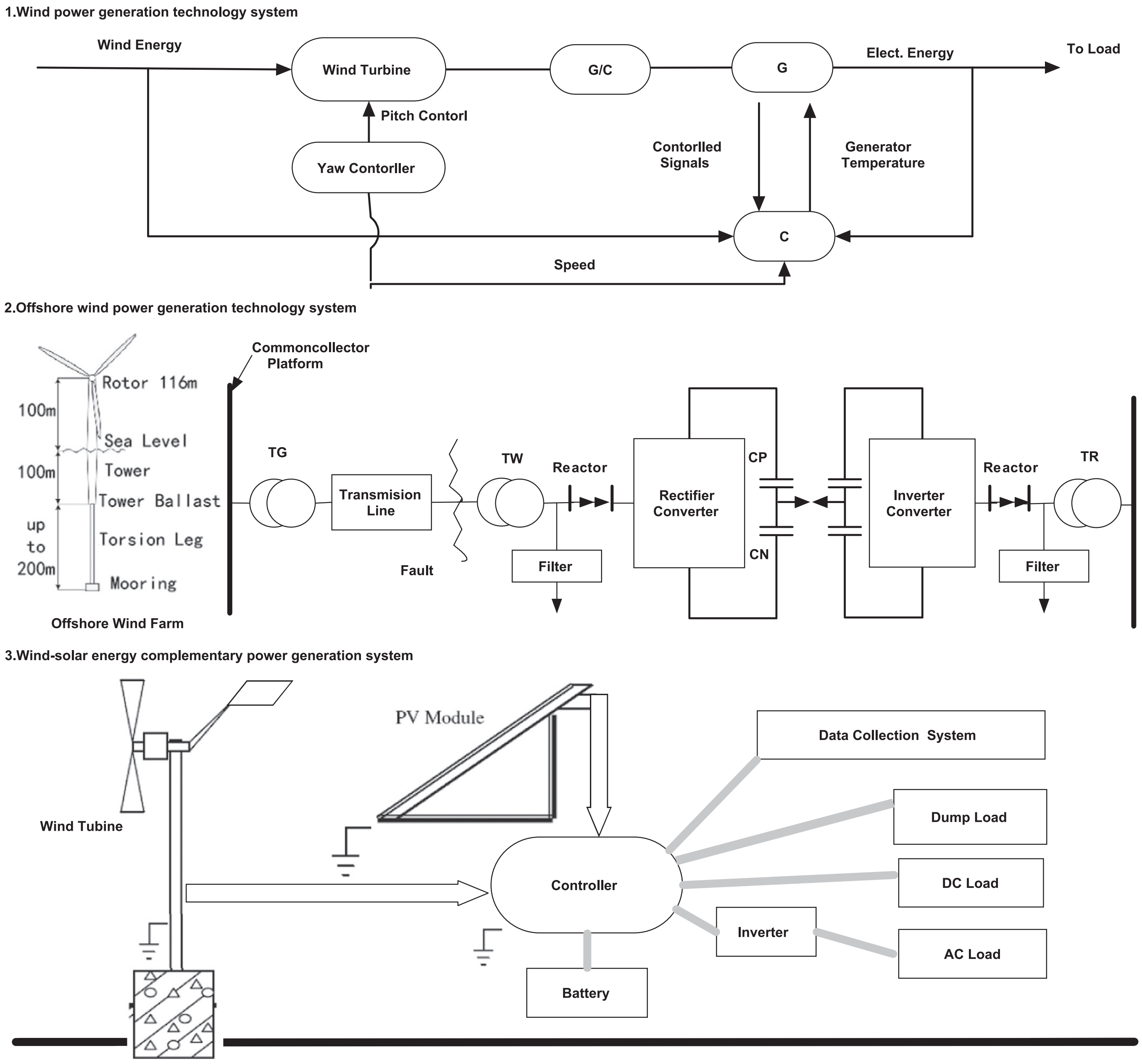

Fig. 8. Three stages of WEGTP.

powered systems, hybrid wind and diesel powered systems, hybrid wind and biomass energy powered systems, hybrid wind energy and hydrogen storage power systems [69], and the most popular hybrid wind and solar energy generation systems.

Wind–diesel systems: these systems are ideal for remote villages, which do not have a connection to a grid. The combination of diesel generators and wind turbine has become an important alternative for a reliable and economic power supply.

Wind–hydro systems: these systems use a mechanical coupling between a wind turbine and an electrical pump. From a wind energy perspective, the electrical coupling of the wind turbine and electrical pump can be regarded a special application of small-or medium-size wind turbines with a power generation unit.

Wind–hydrogen storage systems: the hydrogen is stored in an appropriate high-pressure vessel, and it can be used in a combustion engine, fuel cell or burned in a water cooled burner. When hydrogen and oxygen are burned in a burner, a very high-quality steam is produced. This steam is ideal to use for space heating, or to drive wind turbine to produce electrical output.

Future hybrid energy systems, while maintaining security and reliability, will need to be more flexible on the demand side as well as on the supply side if they are non-polluting, low-carbon energy sources. Even if a wind energy system is not able to directly economically link with the existing energy system, alternative measures need to be taken into consideration to mitigate global warming concerns and ensure energy security.

The most promising hybrid energy system allows for a constant power output all year round through the combination of wind energy generators and photovoltaic cells. Solar energy could be the primary source during the hotter months and wind energy could be the primary source during colder months [70].

Renewable energies are expected to account for nearly half the increase in global power generation by 2035, with wind and solar PV making up to 45% of this expansion [1]. Wind turbines and solar PV have the highest technical potential for the promotion of renewable energy development, but these technologies' abilities to generate electricity should be further strengthened [71]. For example, the design of a pre-processing stage could optimize hybrid solar wind power systems [72]. Therefore, the key power generation systems at the shift stage of the WEGTP are expected to be complementary wind–solar energy arrangements. The merits of the system include the use of renewable energy source without polluting the environment. Generally, the three stages of the WEGTP are outlined in Fig. 8.

4. Evaluation and discussion

In the next two to three decades, the global need for energy is expected to rise, but fossil fuel consumption needs to be reduced, ensuring not only energy security but also ecological balance. The only solution is a transition to a clean, renewable, low-carbon energy system, which uses the most environmentally friendly and cost-effective technologies to improve economic development while ensuring competitive energy prices and high living standards. Wind energy is a main pillar of tomorrow's energy supply.

4.1. The Evaluation of wind energy

Wind energy industrial expansion is seen as a key solution to climate change, air pollution reduction, energy security, and price stability, and could also be the motivation for the development of new industries and employment. Wind energy generates clean and environmentally friendly electricity, creates jobs and reduces risks, such as particulate matter exposure and susceptibility to imported fuel price volatility.

4.1.1. Environmentally friendly

As an environmentally friendly technology, wind energy has made significant contributions to CO_2 emissions reductions in countries that have depended on extracting and exporting fossil fuels. If offshore wind turbines replace electricity generation from fossil sources at a rate, then each MW of wind capacity should displace about 1800 t of CO_2 per year [73]. Further, wind energy uses no water, so in an increasingly clean water stressed world, water availability is vital, especially for countries like China where clean water is highly valuable and scarce. The amount of water used in fossil fuel plants ranges from about 0.2 to 0.6 gal depending on the technology employed [74]. Assuming a 40% capacity factor, 1 MW of offshore wind energy can offset the use of between 0.7 and 2.1million gallons of freshwater per year. The Californian Energy Commission [75] estimated the amount of water consumption needed for conventional power plants as shown in Table 4.

4.1.2. Cost-effective

Generating electricity from the wind makes economic as well as environmental sense. Producing and selling wind derived electricity is no different from any other businesses. To be economically viable, the cost of making the electricity has to be less than its selling price. In every country, the price of electricity depends not only on the cost of generation, but also on the many different factors that affect the market, such as energy subsidies and taxes. Costs have declined as turbines have become larger, more efficient and more reliable. The cost of wind farm electricity is influenced by such elements as economic depreciation, operation and maintenance costs, taxes paid to local and federal authorities, and energy storage components. Generally, the cost of generating electricity can be predicted as shown in Fig. 9.

Table 4
Comparison between conventional and renewable power plants.

Technology	Water consumption		CO_2 emission
	gal/kW h	l/kW h	g/kW h
Nuclear	0.62	2.30	8
Coal	0.49	1.90	964
Oil	0.43	1.60	726
Combined cycle gas	0.25	0.95	484
Wind	0.001	0.004	7
Solar	0.030	0.110	5

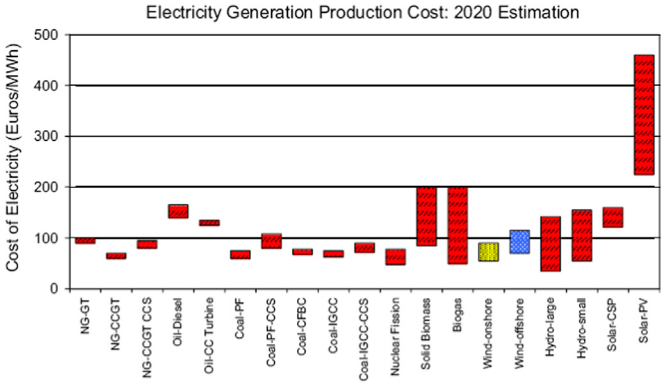

Fig. 9. Electricity Generation Production Cost: 2020 Estimation.

Wind energy installation costs are around US $1.8 million per megawatt for onshore developments and between $2.4 million and $3million for offshore projects. This translates into 0.05–0.09 per kilowatt hour, making wind competitive with coal at the lower end of the range. With subsidies, as enjoyed in many countries, the costs come in well below those for coal — hence the boom in wind energy development [76]. The installation of wind turbines also provides some beneficial effects to the local community and the ecosystem. The turbine foundations placed onto or buried into the seabed create artificial reefs or breeding grounds that have a beneficial effect on local fish populations and benthic communities. Danish studies indicated that socio-economic impacts may be positive. Over 80% of the respondents in a recent Danish study have a "positive attitude towards the establishment of new offshore wind farms". Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found.

Wind energy may become a major source of energy in spite of its slightly higher costs than coal or nuclear power because of the basically non-economic or political problems of coal and nuclear power. That is not to say that wind energy will always be more expensive than coal or nuclear power, because considerable progress is being made in reducing the economic cost. Although the higher economic cost may be widely agreed upon, the fact remains that this result excludes or underestimates the existence of social costs. The threat of global warming and the probability of accidents during the mining, transporting and other phases of conventional energy sources verify the existence of the social cost. If the social costs were included in the total cost, the discussion of "expense" would take a different direction.

4.1.3. Job creators

In the case of the Horns Rev wind site, over 1700 man-years of local jobs were created during the construction period and 2000 man-years were created over the 20-year life of the projects. Approximately, one quarter of these jobs were locally based. These multiplier effects were associated with the construction activities and the manufacturing of materials as well as the indirect effects from demand for the goods and services inputs.

As seen in Fig. 10, wind energy employment in the EU is expected to more than double from 154,000 in 2007 to nearly 330,000 in 2020. Onshore wind energy will continue to be the largest contributor to employment at present, but by 2025, offshore wind energy employment is expected to exceed onshore employment. By 2030, more than 375,000 people are predicted to be employed in the European wind energy sector—160,000 onshore and 215,000 offshore [77].

4.2. Analytical framework for the promoting of wind energy diffusion

On the basis of above research about the role of the technological paradigm for the development of wind energy technology, the analytical framework and some reasonable suggestions are given on technology policy and management. Through this wind energy technological paradigmatic analysis, we now have a good understanding of wind energy technological diffusion. To arrest climate change, a transition to a low-carbon economy must take place quite rapidly, within a century at most. Thus, the rate of new technologies diffusion, such as those for the generation of electricity from wind energy sources becomes a central issue. The analytical framework for the promotion of wind energy diffusion is shown in Fig. 11.

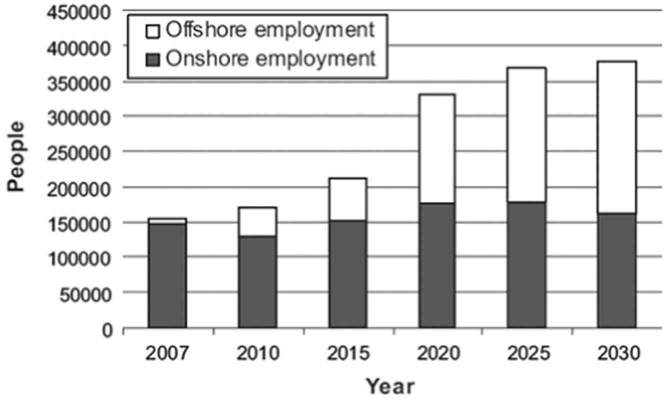

Fig. 10. Wind energy sector employment in the EU.

4.2.1. Build up the technological paradigm

The technological paradigm plays a very important role in setting the framework for research by defining "the rules of the game", although this may occur completely unintentionally. Indeed, as Dosi points out, technological paradigms tend to have a very strong "excluding effect" which limits the efforts and technological imagination of the engineer, as well as that of the entire organization, thus making them blind to other technological possibilities.

When a new technological paradigm appears, it represents a great discontinuity or a change in the technological trajectory. This change may be related to a radical innovation which introduces new technology. Dosi mentions the transition from thermo valve to semiconductors in electronics as an example. This change required new handling and manufacturing principles, new materials and the establishment of a whole group of new tasks. Similarly, in the field of wind energy technology, the transition from onshore wind generation to offshore wind generation is another example of the changes which the technological paradigm brings. The offshore wind turbine requires new materials, new scientific principles and new control systems, and faces completely new problems.

4.2.2. Wind energy policy

The biggest hurdle for the wider diffusion of wind energy technology is its high initial investment capital cost. With respect to this issue, it has been strongly recommended to internalize the environmental externalities in that sense—for example by means of applying carbon taxes to fossil fuels. Studies have shown that there is a correlation between the diffusion parameters and the composite policy index [78]. Energy policy plays a vital role in mitigating the impact of global warming and alleviating the energy availability crisis. Policies which encourage more efficient

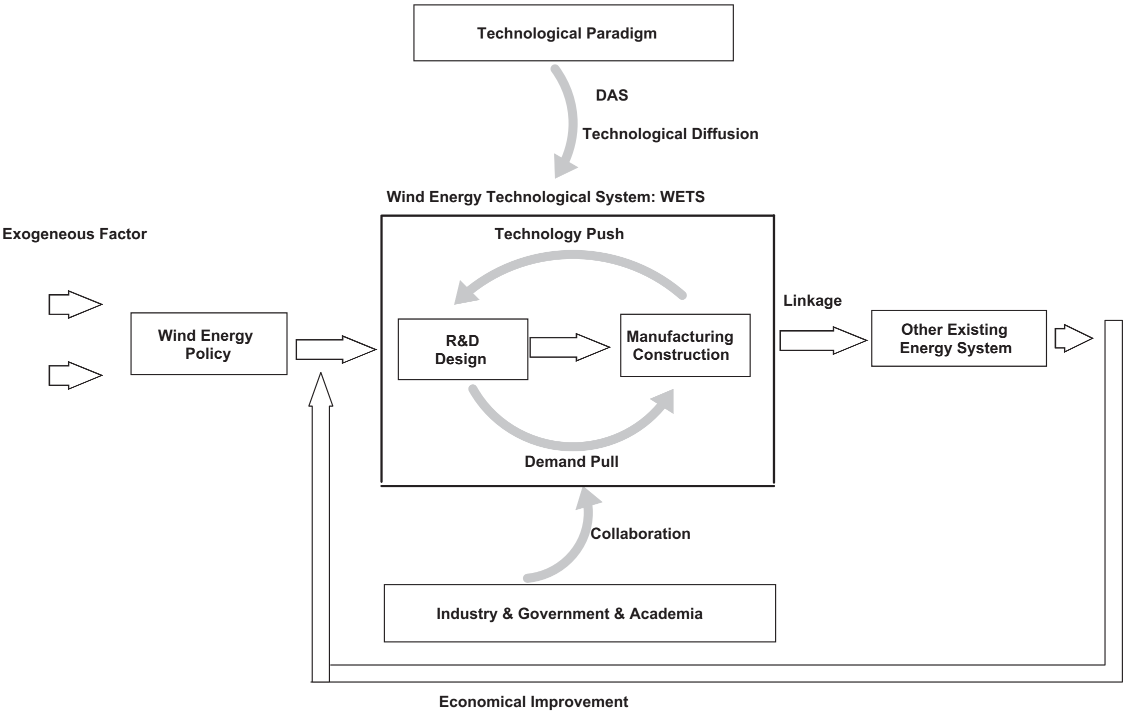

Fig. 11. The analytical framework for the wind energy generation industry.

Table 5
Summary of wind energy policies in different countries.

Country	Principle support (FIT/RPS)	Investment support	Sales or energy tax exemption	Public loans/ financing	Legislation	Target implementation	R&D support	Strength (highlight)
USA	RPS	Yes	Yes	Yes	Yes (25%,2025)	Yes(25% of supply, 2025)	Yes	Investment & production tax credit
Canada	FIT	Yes		Yes	Regulatory Framework in 2008	Yes, (12 GW, 2016)	Yes	Production incentive of 1 cent/kWh for the first 10 years
Denmark	FIT(1993)	Yes	Yes		Yes (50%,2030)	Yes (200 GW, 2030)	Yes	Tender schemes for off-shore wind
Germany	FIT(1991)	Yes		Yes	Yes (20%,2020)	Yes (30 GW, 2010)	Yes	Electricity feed-in tariff
Turkey	FIT(2005)	Yes				License up to 10 GW		Preparing to join the European Union
Australia	FIT	Yes		Yes	Yes (60%,2050)	Yes (10 GW, 2020)	Yes	National Clean Energy Target
China		Yes	Yes	Yes		Yes (30 GW, 2020)		Locally made components
Japan	RPS(2003)	Yes			Yes (6%,2012)	Yes (3000 MW, 2010)	Yes	Market incentives and subsidy
Korea	FIT(2002)					Yes (2250 MW, 2012)	Yes	Feed-in-tariff system
Egypt	FIT	Yes		Yes		Yes (7.2 GW, 2020)		Guarantee of a long-term power purchase agreement
Algeria	FIT	Yes		Yes	Yes (40%,2020)	Yes(10–12%, 2010)		CSP Global Market Initiative
Spain	RPS	Yes		Yes		Yes(12%, 2010)	Yes	Localization rate
India	FIT	Yes	Yes	Yes		Yes (11 GW, 2010)	Yes	Build unconventional department of energy

technologies and use of energy could contribute almost 80% to the desired lowering of CO_2 emissions by 2030, with the remainder gained from fuel substitution. Regional and local energy policies can have substantial effects on energy and other markets even beyond the countries directly concerned [79]. From research, it has been found that Feed-In-Tariffs (FIT), Renewable Portfolio Standards (RPS), incentives, pricing laws and quota systems are the most useful energy policies practiced in many countries around the world. Some wind energy policies for different countries are shown in Table 5.

Energy policy could assist in increasing the use of wind energy generation as well as in stimulating the energy generation industry. The Chinese government has thrown its considerable weight into exploiting wind resources, and the trend of related policies towards wind power generation in China is shown below in Table 6. "It is its flagship for the renewable-energy industry, so the government is going to support it," says Wu [80]. Wind energy policy differs between nations according to circumstance and national objectives, but many of the issues require international cooperation. All nations share the planet's atmosphere, and all would benefit from reduced pollutant emissions. As wind energy plays such a vital role in society, it is important that government policy, science and technology work together harmoniously as global energy security problems can be solved if all three components work together. Policy determines what is acceptable, science shows what may be possible, and technology demonstrates what, within acceptable constraints, is practicable [81]. Sustained public policies and the monitoring of technological performance are needed to support further progress in a variety of low-carbon technologies for electricity, transport and heating until they can support themselves [82].

4.2.3. *Industry–Government–Academia Collaboration*

To promote wind energy diffusion, economics is important. For example, investment costs should be redeemed through the benefit obtained by wind energy generation. To ensure a return on investment, both equipment and economies of scale need to be enlarged. While the demand for quality and safety is high in the wind energy generation market, the value is relatively low. Although the electricity generated by wind energy is now approaching a profit, there are still several economic efficiency problems.

The need for global warming mitigation can focus future supply needs on wind energy innovation, which can coexist with other existing energy systems. Government, industry and academic organizations need to work together to solve the above-mentioned problems as these are not solely industry problems.

Technological development needs to be focused on through industry, government and academic collaboration to guarantee safety, performance improvement and manufacturing cost reduction so as to ensure technological market penetration. Industry works with manufacturers to find suitable solutions to reduce installation costs, and, in parallel, the government supports the wind energy system installations through the provision of suitable policies and incentives to enable wind energy systems to have a competitive edge. Through these efforts, the running costs can compete with other existing energy systems on a net present value basis.

5. Conclusions

Considering the need for an ecological civilization, low-carbon methodologies are beginning to have an impact on power generation, such as in the exploitation of renewable and new energy sources. However, up to now, there has not been a wind energy

Table 6
Transition of wind energy policy in China.

Year	Wind energy policy
1994	The former Ministry of Power issued a policy statement entitled "Opinion on Wind Power Farm Construction and Management", and Chinese wind power policy start developing.
1998	The Regulation about the Management of Grid-Connected Wind Farms issued by MOEP, and the Chinese (on-grid) wind power industry was established.
2003	The "Tariff Reform Program" established a mechanism that combined guaranteed demand with competition.
2005	The first "Renewable Energy Law", issued in 2005, went on to define the strategic priorities and responsibilities for the development of wind energy.
2006	"Regulation on Prices and Cost-Sharing in Renewable Energy" issued which states that wind power prices are to be set by the government, with two alternative pricing modes.
2007	• "Approach of Grid Enterprises Purchasing Renewable Energy Electricity" was issued in September 2007. The Plan established technology specific targets, including a 5 GW target for grid-connected wind power by 2010, and 30 GW by 2020 (of which 1 GW was designated for offshore wind power). • The Ministry of Finance issued "Guidelines on Adjusting Import Taxes on High-Voltage Wind Turbines and Components"
2009	• The National Development and Reform Commission (NDRC) Notice on Policy to Improve Grid-Connected Power Pricing for Wind Power Generation. • Amendments to the Renewable Energy Law were passed.
2010	NDRC introduced the first policy governing offshore wind development in China, the Outline Measures for the Administration of Offshore Wind Power Development.
2011	"The Wind Farm Connecting Power Systems Technical Regulations" were formally approved by the National Standards Committee.

technological paradigmatic framework, though some work has been done on low-carbon economies. After combining the technological paradigm with wind energy development, we proposed the WEGTP.

The wind energy development technological paradigm was established in combination with demand-pull and technology-push theory. Three phases were identified with the assistance of a novel data analysis system with onshore wind energy generation technology in the competition stage, offshore wind energy generation technology in the diffusion stage, and the hybrid wind and solar energy generation technology in the shift phase. From the WEGTP, we were able to speculate on the future development in wind energy generation technology. Further, this article proposed a novel mathematical WEGTP diffusion model that provided an explanation for wind energy technological development. The well-known S-shaped curve was shown to reflect the three WEGTP phases, and the model for the technological evolution of wind generation demonstrated that wind installed capacity diffusion velocity peaked in 2012. Finally, we gave a few suggestions as to how wind energy technological diffusion can be better promoted by the development of a hard path and soft path. The technological paradigm lays the basis for the hard path, but also paves the way for the soft path that includes government policy, efficient technologies, and human capital.

The research in this paper may have the potential to significantly influence our future energy needs and provide new future research ideas to scholars. However, many uncertainties still exist, so further work is necessary to evaluate the individual cases selected in this study in the shift phase which could be possibly extended to other new and renewable energy technologies.

Acknowledgments

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