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Technology S-curves in wind energy: a comparative analysis

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Abstract. The use of a mathematical tool such as the logistic curve to analyze the performance of wind energy and public investment in R&D by different countries throughout the history of the technology has allowed this study to draw conclusions on how the different countries studied have dealt with the problem of technological obsolescence.

Key words. Wind Energy, Technological forecasting, R&D investment, LCOE (Levelized Cost of Electricity), S-curve.

1. Introduction

The disparity of historical stages in which the countries of the USA, Germany, China, and Spain have developed their wind power technology has enriched a study that follows the course of action of a technology that seems to have a new path in offshore. This study is an extension of a 2009 study by Pr. Melissa A. Schilling on renewable energy technology forecasting [8]. These countries have been chosen for their importance in their own context, as the USA is the country with the highest GDP, Germany is the European leader in wind energy investment [1], China is already the second biggest world economy and the most populated, and Spain is a country with a huge potential in wind energy. The opinion of different experts has also been key in drawing up a series of conclusions that are intended to serve as a reference for possible future lines.

Firstly, a brief and simple explanation will be given of the mathematical model used to analyze the performance of wind energy for each country studied. Logistic curves, or S-curves, try to quantify how a parameter evolves versus time (or another parameter that depends on time). In this way, the evolution of the price of energy versus the investment undertaken can be observed.

The bulk of the study will cover an analysis of the investment undertaken by the country of the United States, Germany, China, and Spain. The article will address both historical investments in wind energy and technological patents in R&D over time, where even different sources of different technology reports will be compared to see which approach is more interesting in terms of energy production costs and to see the evolution of the technology over time and investment.

Finally, a series of conclusions about the study will be drawn and some possible future directions will also be discussed.

2. S-Curves

The mathematical model that has been used in this study to construct the curves that will show the growth in terms of wind technology performance will be that of the logistic function also called S-curve. The curve has three phases, a first fermentation stage, a growth and maturation stage, and finally the saturation or obsolescence stage. These curves follow the following equation, where L represents the limit of the curve and β is L/2; α represents the slope of the curve [9].

$$f(x) = \frac{L}{1 + e^{-\frac{\ln(81)}{\alpha}\cdot(x-\beta)}} \qquad (1)$$

It will be important to differentiate the phases present within a logistic curve. As its name indicates, they are S-shaped, and within it four phases could be defined. First, the fermentation phase, where the evolution is slow and rapid results are not seen. Then, the growth and maturation phases, where the evolution is linear [3]. Finally, a saturation phase, in which the technology's performance begins to stagnate despite the investment made.

The end of each curve occurs in the saturation phase, where improvement no longer takes place, but innovation is necessary to jump to a new curve, thus giving rise to the phenomenon of self-similarity. This fact implies that there are infinite S-shaped curves within a logistic curve [3].

3. Background

The result of the large investment in renewable energies undertaken by the United States since the early 1970s has placed the American country in a favorable energy position compared to other countries [8], since they were the pioneers in wind power development. The case of China, however, is quite the opposite of the American case. The Asian country started its strong development of wind technology from 2000, with the new millennium [2]. Since then, with a very strong policy of creating new technological patents in the wind sector, as will be seen below, they have managed to catch up with the American country.

With a very different development from that of the countries of China and the United States, the developments in Germany and Spain are also analyzed. In the case of Germany, development was slow, progressive but steady. A series of regulatory policies to favor development, and programs such as "Grosswindanlage" [1] created new turbines. These policies had a large investment, and ended up being overtaken by new innovative programs, which resulted in an overspending problem. In the following section, it will be assessed whether the "Energiewende" program is being successful or not. In the case of Spain, the development of wind energy has experienced a strong development thanks to the geographical situation of the country, which favors this technology. This, together with the European reference in Germany, has allowed a rapid advance in the return on investment.

4. Sources

The price of generating wind energy is measured by the LCOE (Levelized Cost of Energy/Electricity). It represents the cost of generating energy over time versus the energy produced in the same period. This parameter has been chosen to demonstrate the effect of technological progress graphically and visually, since the higher the efficiency, the higher the LCOE in this study. One might think that we are dealing with a simple concept, but one should be aware for a moment of the amount of costs that could be considered. These costs are not only primary costs but also other types of costs, such as personnel, maintenance and material or transportation costs.

Energy agencies such as NREL, IRENA, Lazard and many others are responsible for reporting on LCOE. In this section some of them are considered to exemplify one of the major difficulties of this work, finding reliable sources and a wide range of data. A simple example graph in Figure 1 then analyzes the LCOE on a global scale for any given year for wind power. The difference is self-evident, the difference between Lazard and the IPCC source increases by such a significant percentage that it seems that we are talking about a different parameter. If you visualize that a medium/large city could consume about 1 MW, if one wanted to feed this city only with wind energy (and in the case that this was possible) according to Lazard it would cost about 33% cheaper than according to the IPCC source. By quantifying some costs and others, an error is being made between these sources that could well be compared to the energy that could be consumed by two, three or even more small towns compared to the medium/large city. The solution, undoubtedly, is to standardize these costs and not to mix sources.

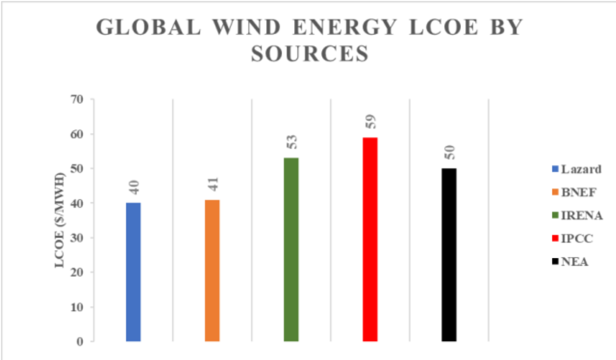

Figure 1. LCOE Sources example.

Not all countries have such a large and reliable amount of data as the United States, and at times it is difficult not to be tempted to mix sources where one report goes up to 2016, and another starts in the same year. This is a major mistake, as the logistic curve would show a change of trend in technology when really the drop/rise in LCOE is only due to a change of source. Moreover, to make the error bigger, since the change would occur in an apparently strange year since no technological or economic event happened at that time, one could try to justify it with totally out-of-context reasons. For this reason and speaking now of the methodology followed in this study, different paths have been taken to obtain complete graphs, with a horizontal axis that allows a broad study and not just a few years. For the rest of the countries other than the United States, it has been chosen to use the number of patents as a measure of the horizontal axis, since a patent is a very useful measure for S-shaped curves [4] [6].

The software used to elaborate the curves will be Loglet Lab, which offers a fast modeling of the S-Curves. The algorithm will use as a model the logistic cumulative function, which follows the following formula. In each country section studied, a table with the chosen parameters is represented [12].

$$y = \frac{K-d}{1+e^{-r(t-t_m)}} + d \quad (2)$$

5. Results and Analysis

In this part of the document the results of the curves showing evolution of LCOE in function of R&D investment (money or patent) from the countries studied will be shown and analysed.

The most relevant aspect of the United States section has been the comparison of two curves from data from different reports. First, the curve was made for the IRENA report, and second (Figure 2) for NREL. The IRENA curve was discarded as it considers factors that are not purely technological. For other countries, however, it will be the only source that allows us a wide range of data. Being able to see what a bump is and how the curve can behave in the face of it has been very useful. Also, to see how the United States, besides being a country that decides to allocate a large part of its budget to research, does so intelligently, since there is no great difference between the slopes of different waves, which is undoubtedly the greatest challenge when developing a technology. It should be noted that it has been possible to carry out this report comparison thanks to the large amount of existing data for the United States, which for a research work is to be appreciate.

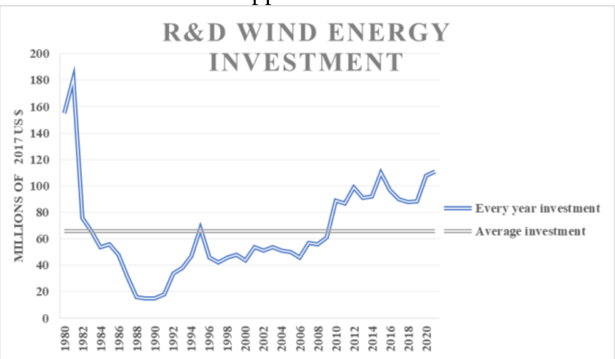

Fig. 2. US R&D Wind Energy Investment

Since the United States began its investment policy in the early 1970s, it has led the development of technology. In the curve, three waves with different paradigm shifts can be observed without an excessive technological bump, thus creating a smooth development thanks to the early investment of the American country [8]. Within the second or developmental phase, there are different results. The United States follows a development very marked by the phenomenon of self-similarity, with continuous paradigm shifts and overcoming them without apparent difficulty. Such changes may be due to technological potholes that have been solved with further research, such as for example the increase of height inside turbines throughout history to increase power.

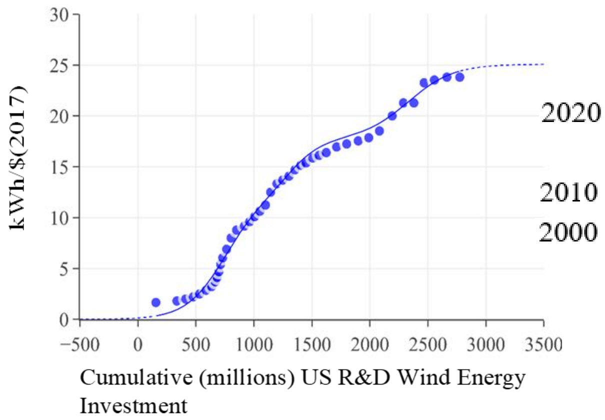

Fig. 3. S-curve of LCOE in function of cumulative (millions) US R&D Wind Energy Investment

	1st Wave	2nd Wave	3rd Wave
d	0	0	0
K	17.4	17.4	17.4
tm	591.58	1464.75	2774.5
r	0.0077	0.0119	0.00814

This is followed by China. In this case, the number of patents will be used as a measure of the horizontal axis. Certainly, the analysis of China does not present a wide range of years, we could even say that there is not too much data from the fermentation phase of the technology, but it will certainly be possible to establish a series of comparisons that will allow us to draw some very pertinent conclusions. It is impressive to be able to contemplate that the number of patents in 2018 exceeded the value of 8500. When talking about patents we are also considering the efficiency in terms of investment, since it is not the same to turn 100 million $ into 5000 patents than to turn them into 8000, and it certainly seems that China's efficiency in terms of its investments is high. The energy price levels are taken from IRENA reports [10].

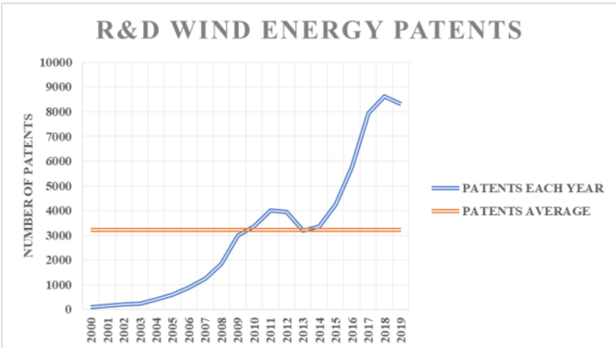

Fig. 4. China R&D Wind Energy Patents (IRENA)

China's development is impressive. The fact that its average number of patents per year is more than 3,000 is astounding compared to other countries. For this country, the fact that it started late in the development of technology, back in the year 2000, has not meant any setback. However, the forecasts for this country are not promising, following the line of the rest, and it is predicted that if there is no new paradigm shift, the technological ceiling will have already been reached [2]. Talking about the fermentation phase, big differences can be observed. Undoubtedly, the country that shows the most different fermentation phase from the rest is China, caused by the late start and the heavy investment and quick catch-up of the technology. With a huge public investment, they were able to reach the levels of the rest of the countries thanks to their technological reference [2].

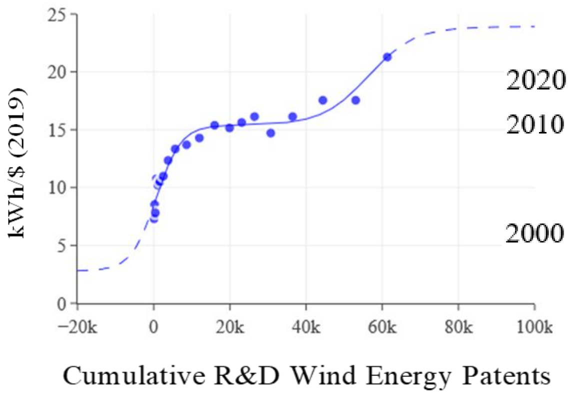

Fig. 5. S-curve of LCOE in function of cumulative R&D Wind Energy Patents for China

	1st Wave	2nd Wave
d	0	0
K	15.7	13.1
tm	176	64036
r	0.000332	0.000151

We now turn to the number of patents that Germany has developed since 2000. Like investments, they are neither linear nor do they follow any established or apparently predictable pattern. However, it is true that they are not too far from the annual average of about 475 patents, with the highest record being about 725 and the lowest about 300, but still well below China. The energy price levels are taken from IRENA reports [10].

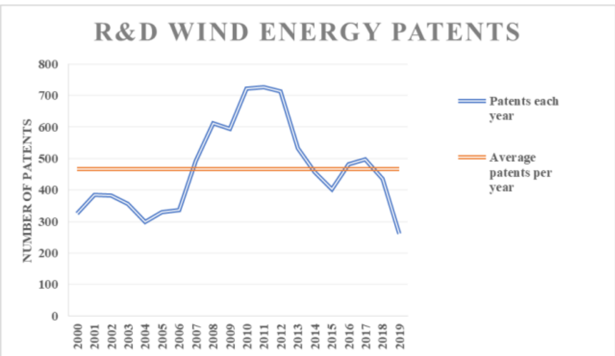

Fig. 6. Germany R&D Wind Energy Patent (IRENA)

It can be seen how in the long term, Germany's investment plans have been constantly truncated by new paradigm shifts, creating unnecessary expenditures [1].

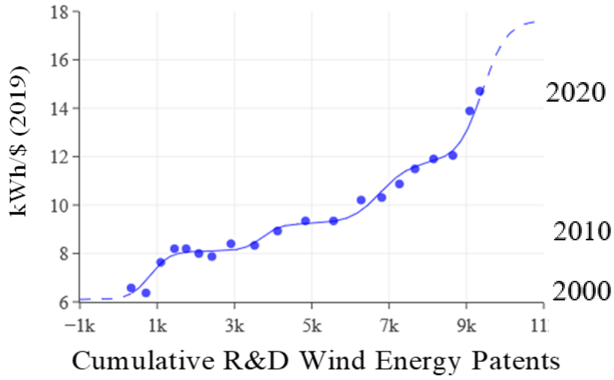

Fig. 7. S-curve of LCOE in function of cumulative R&D Wind Energy Patents for Germany

	1st Wave	2nd Wave	3rd Wave	4th Wave
d	5.84	0	0	0
K	8.3	1.27	1.78	5.12
tm	703	4244	6865	9145
r	0.0022	0.00298	0.00249	0.00292

The above curve presents a very important problem that had not been presented previously in the study. There are several points that do not follow the progression of the rest of the LCOE samples over the years in Spain. It is because of these points that the curve is distorted, and its analysis is completely useless. This is because to calculate the LCOE this source has considered extra-technological factors that do affect the price of energy, but not only its development. To solve this problem, these points have been eliminated from the graph, so it is very important to understand that despite a curve that allows analysis since it is not distorted, it is not a real curve, since not all the real historical data of the LCOE in Spain are being shown. The energy price levels are taken from IRENA reports [10].

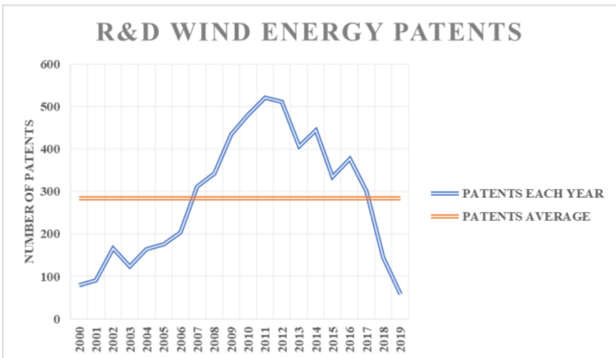

Fig. 8. Spain R&D Wind Energy Patent (IRENA)

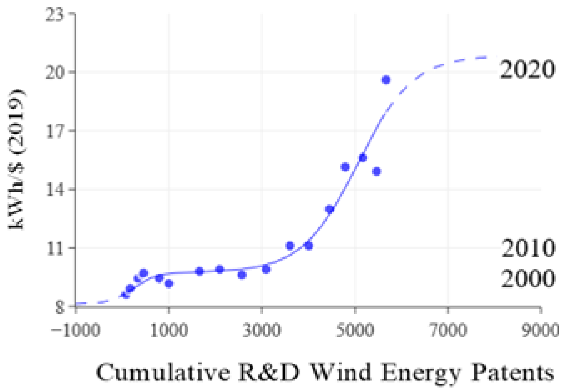

Fig. 9. S-curve of LCOE in function of cumulative R&D Wind Energy Patents for Spain

d	8.2	0
K	9.91	12.2
tm	198	5036
r	0.00294	0.00179

4.Conclusions

Thanks to this analysis and the collaboration of experts such as François Cauneau (Deputy Director of Mines-ParisTech Sophia Antipolis and Professor of Fluid Mechanics at Mines-ParisTech) and others, some conclusions can be drawn.

- Researchers are already trying to implement new onshore turbine designs that have higher heights, but perhaps this time bigger no longer means better, because as height is gained, wind force related phenomena come into play that were not addressed years ago, so it is likely that the most efficient point of turbine height has already been reached.

- The development of offshore wind energy arises at this point. With new designs like vertical turbine axes created by different technology companies and models already implemented in the North Sea, more power is expected to be installed in the coming years, creating a new paradigm in the development of the technology. However, the same mistakes that could be made in the past should not be made. Investment must be slow, thoughtful, and staggered so as not to end up indebting citizens.

- The United States and China have achieved a more efficient development of the technology than Germany. Germany has been affected by its own aid to subsidize wind energy with different programs, and this has caused a development full of phases that have slowed down progress. Spain is in a more complex situation, since it follows the German investment model because it belongs to the European Union, but it enjoys a privileged geography and orography that have allowed it to develop the technology quickly once the first wave of the economic crisis has been overcome.

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