Analysis of productivity in the Spanish wind industry

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ABSTRACT

This paper provides an empirical analysis of the evolution of total factor productivity (TFP) among Spanish wind farms. The Malmquist productivity index (MPI) is used to measure how productivity evolves. The index makes it possible to break down total productivity performance into the components of technological change and changes in technical efficiency. Technical efficiency is then further broken down into changes in purely technical efficiency and changes in scale efficiency. The analysis is carried out by estimating two alternative models, which enables us to assess the impact of the different kinds of technology used on the wind farms.

From the results, we conclude that it is important to model the way in which the farms use different kinds of technology. Including technology as an additional input allows us to correct the estimations of changes in productivity and its components. Once these estimations have been corrected by including the different technologies utilized, the results indicate that growth in productivity (around 2% annually) is mainly due to changes in the technical efficiency growth rate, specifically in the component of pure technical efficiency.In contrast, the technical change component does not contribute to growth in productivity, indicating that technological capacity has not been optimized on most wind farms. It should be highlighted that,while the results of productivity are fundamentally conditioned by the technology variable, they are also affected by variables which are exogenous to the productive processes.In light of these results, policy implications are discussed.

Keywords: Wind energy, Total factor productivity, Technological change, Pure technical efficiency, Scale efficiency, the Spanish wind industry

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1.Introduction

Since the end of the 20th Century, renewable energies have been evolving rapidly worldwide, and wind power has been in the vanguard of this change. This dynamic may be ascribed to a number of factors, but the foremost of these is undoubtedly the establishment of policies that aim to foment more sustainable development through the use of renewable energies[1-5]. In terms of installed capacity, the proportion of wind power generation has risen from 9.7% in 2007 to 23.7% in 2016 (Table 1). This reflects the dynamic status of an emergent industry in the vanguard of global strategic energy production and, consonant with this intensification, the wind power industry has come under the lens of numerous analysts, e.g., [6-8]

Table 1
World renewable energy installed capacity (on-grid)
Source: author´s elaboration from Irena [9].

	Hydropower		Marine energy		Wind energy		Solar energy		Bioenergy		Geothermal		Total
Year	MW	%	MW	%	MW	%	MW	%	MW	%	MW	%	MW
2007	801 783	83 .0	267	0 .0	93 553	9 .7	9 157	0 .9	52 499	5 .4	9 144	0 .9	966 403
2008	833 465	80 .5	267	0 .0	119 666	11 .6	15 188	1 .5	56 899	5 .5	9 464	0 .9	1 034 949
2009	862 488	77 .7	269	0 .0	150 142	13 .5	23 360	2 .1	63 701	5 .7	9 903	0 .9	1 109 863
2010	884 500	74 .5	271	0 .0	182 684	15 .4	40 164	3 .4	69 413	5 .8	10 125	0 .9	1 187 157
2011	911 024	70 .6	525	0 .0	222 052	17 .2	71 743	5 .6	74 740	5 .8	10 015	0 .8	1 290 099
2012	941 540	66 .9	528	0 .0	271 714	19 .3	101 938	7 .2	81 412	5 .8	10 482	0 .7	1 407 614
2013	983 530	64 .4	527	0 .0	303 675	19 .9	139 284	9 .1	88 794	5 .8	10 787	0 .7	1 526 597
2014	1 019 534	61 .7	527	0 .0	350 225	21 .2	176 707	10 .7	94 516	5 .7	11 457	0 .7	1 652 966
2015	1 053 948	58 .3	533	0 .0	415 304	23 .0	224 791	12 .4	101 108	5 .6	11 848	0 .7	1 807 532
2016	1 083 495	55 .0	536	0 .0	466 505	23 .7	295 664	15 .0	109 731	5 .6	12 628	0 .6	1 968 559

In spite of a systemic crisis and the consequent negative impact on the traditional model of financing renewable energy installations, the most recent reports, IRENA [9] and WWEA [10], allow us to confirm the strength of the eolic sector and a significant concentration of wind power generation within five countries (Table 2). Specifically, if we take 2016 as a reference year, the five countries set out in Table 2 represent more than 71% of worldwide installed wind capacity. China is the leading nation with respect to wind installed capacity (31.9%), followed by the U.S. (17.4%), Germany (10.7%), India (6.2%)and Spain (4.9%). Within this global context, the relatively recent ascent of China as a producer of eolic power is especially noteworthy and has been characterised by the Chinese government's support for their own specific model of wind power production[11]. In contrast, in the case of Spain, the development of the industry has been seriously shackled by the lack of an integrated regulatory framework for the industry[12]and, from 2012 onwards by the effects of the brusque changes in the normative regulations controlling the industry[13].

Table 2
World leader wind installed capacity countries.
Source: author´s elaboration from IRENA [9].

	China		EEUU		Germany		India		Spain		World	Rest World	
Year	MW	%	MW	%	MW	%	MW	%	MW	%	MW	MW	%

2007	6031	6 .4	16 515	17 .7	22 183	23 .7	7 845	8 .4	14 820	15 .8	93 553	26 159	28 .0
2008	12174	10 .2	24 651	20 .6	23 815	19 .9	9 655	8 .1	16 555	13 .8	119 666	32 816	27 .4
2009	17672	11 .8	34 296	22 .8	25 692	17 .1	10 926	7 .3	19 176	12 .8	150 142	42 380	28 .2
2010	31410	17 .2	39 135	21 .4	27 180	14 .9	13 065	7 .2	20 693	11 .3	182 684	51 201	28 .0
2011	48046	21 .6	45 676	20 .6	29 060	13 .1	16 084	7 .2	21 529	9 .7	222 052	61 657	27 .8
2012	62956	23 .2	59 075	21 .7	31 304	11 .5	18 421	6 .8	22 789	8 .4	271 714	77 169	28 .4
2013	76560	25 .2	59 973	19 .7	34 660	11 .4	20 150	6 .6	22 958	7 .6	303 675	89 374	29 .4
2014	96370	27 .5	64 232	18 .3	39 193	11 .2	22 465	6 .4	22 975	6 .6	350 225	104 990	30 .0
2015	129340	31 .1	72 573	17 .5	44 670	10 .8	25 088	6 .0	22 983	5 .5	415 304	120 650	29 .1
2016	148640	31 .9	81 312	17 .4	49 747	10 .7	28 875	6 .2	22 992	4 .9	466 505	134 939	28 .9

In Spain, regulations affecting the generation of wind power vary considerably depending on the autonomous region. Four of these regions have been at the forefront of the development and evolution of wind power since 1995; Galicia, Castile and León, Castile-la Mancha and Andalusia. These are the regions whose wind power sector has evolved most notably and whose weight as a proportion of total Spanish production has been the greatest by far in recent years. In fact, the combined production of the four regions represents 70% of the total capacity for Spain in 2016 (Table 3).

Table 3
Installed eolic potential in each of the Spanish regions (MW)
Source: Own elaboration from AEE [14] and IAEST [15].

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Spain	15011 .87	16740 .33	19148 .81	20676 .05	21673 .51	22785 .10	23659 .20	22986 .70	22988 .40	23027 .70
Andalusia	1459 .71	1794 .99	2840 .07	2979 .33	3066 .93	3263 .20	3337 .70	3337 .70	3337 .70	3338 .00
Aragón	1723 .54	1749 .31	1753 .81	1764 .01	1811 .31	1888 .80	1893 .30	1893 .30	1893 .30	1893 .30
Asturias	277 .96	304 .30	355 .95	355 .95	428 .45	512 .50	518 .50	518 .50	518 .50	518 .50
Balearics	3 .65	3 .65	3 .65	3 .65	3 .68	3 .70	3 .70	3 .70	3 .70	3 .70
Canaries	0 .00	134 .09	138 .34	138 .92	145 .78	160 .10	165 .10	176 .60	176 .60	182 .00
Cantabria	17 .85	17 .85	17 .85	35 .30	35 .30	38 .30	38 .30	38 .30	38 .30	38 .30
Castile and León	2818 .67	3334 .04	3882 .72	4803 .82	5233 .01	5510 .60	5560 .00	5560 .00	5560 .00	5593 .00
Castile-Mancha	3131 .36	3415 .61	3699 .61	3709 .19	3736 .79	3806 .50	3806 .50	3806 .50	3806 .50	3807 .00
Catalonia	347 .44	420 .44	524 .54	851 .41	1003 .35	1258 .10	1267 .10	1268 .90	1268 .90	1269 .00
Valencia	590 .94	710 .34	986 .99	986 .99	1169 .99	1189 .00	1889 .00	1189 .00	1189 .00	1189 .00
Galicia	2951 .69	3145 .24	3231 .81	3289 .33	3272 .17	3311 .50	3314 .10	3328 .30	3330 .00	3330 .00
Murcia	152 .31	152 .31	152 .31	189 .91	189 .96	263 .00	262 .00	262 .00	262 .00	262 .00
Navarre	937 .36	958 .77	961 .77	968 .37	976 .92	979 .90	1004 .00	1004 .00	1004 .00	1004 .00
Basque Country	152 .77	152 .77	152 .77	153 .25	153 .25	153 .30	153 .30	153 .30	153 .30	153 .30
The Rioja	446 .62	446 .62	446 .62	446 .62	446 .62	446 .60	446 .60	446 .60	446 .60	446 .60

Note:The small differences between Tables 1 and 2 that appear for the total for Spain are due to the different databases, which use distinct statistical accounting methods.

Presently, the wind industry is playing an important role throughout the world since it is providing new employment opportunities, diversifying the sources of energy production, contributing significantly to sustainable development and helping to mitigate climate change [16-18]. In the last fifty years, wind power has come to the fore for numerous reasons; it generated 1.2 million jobs in 2018, the installed capacity has risen vertiginously [19], it has become a consolidated industry in and of itself [17] and is a key component in the machinery of climate change adaptation and mitigation [18]. Wind energy accounted for 63% of investment in renewable energy in 2018, up from 52% in 2017 [5]. Wind energy for the production of electricity today is a mature, competitive, and virtually pollution-free technology widely used in many areas of the world. The generation of electricity from wind is not susceptible to depletion in the same way as fossil fuels and, in this sense, its price should remain relatively stable. The obvious advantages include wresting the need for various billions of barrels of oil and the climate damage that comes with burning fossil fuels[4]. In terms of installed wind capacity (Table 2), Spain is now one of the leading five producers in the world, a status which has come at a certain cost. Nevertheless, the wind industry in Spain now provides 19% of all of the energy consumed in the country, generates 22,578 jobs, and prevents the emission of 25 million tonnes of CO_2 each year [20].
Wind energy is expected to play an increasingly important role worldwide, progress that will be driven by a combination of more intensive exploitation and technological improvements [21]. Therefore, for countries such as Spain, an effective analysis of the productive performance of the industry would seem to be essential. This would allow those involved to detect the deficiencies in the industry, put forward measures to correct them and to design policies aimed at improving the productive structure. If this were more efficient, it would be easier for Spain to fulfil the objectives set out by the EU for the year 2030 in which at least 27% of final energy consumption should be generated by renewable sources [22].

At the international level, there are many empirical studies that look at the efficiency of the wind industy, e.g., [23-25]. However, in Spain, despite the burgeoning importance of this sector in recent years, there have been few studies of this nature. There are two papers that look at the region of Galicia in northwest Spain [26,27] but there are none that analyze the total factor productivity (TFP) of wind farms nationally, throughout Spain.

In consequence, this study is novel since it carries out an empirical analysis of the evolution of total factor productivity (TFP) in the Spanish wind industry. The sample is made up of the 96 wind farms located throughout Spain in those regions where wind power production plays a significant role. Additionally, the study utilizes the Malmquist Productivity Index, a highly flexible type of methodology, which allows the analyst to break down the TFP component into its main subcomponents. These are; changes in technology, changes in pure technical efficiency and changes in scale efficiency. The index also reflects the impact of specific forms of technology on productivity. Its flexibility means that the productivity of each wind farm may be broken down according to regional location, type of technology and annual results.

The structure of the paper is as follows. In Section 2 we briefly present the analytical methodology used together with a description of the statistical information. The results we obtain and a discussion of their implications are contained in section 3.The last section offers key findings and policy implications that can be derived from the results.

2. Methods and material

The analysis of total factor productivity (TFP) is a good tool for assessing the performance of wind farms since it is capable of assessing how they assign resources in order to generate production[1]. The type of methodology utilized in order to analyze the behaviour of TFP depends principally on the statistical information available. In our study, we use the Iberian Balance sheet Analysis System (SABI) database[2].The vast majority of studies that use SABI database to analyse productivity also use the nonparametric method of Data Envelopment Analysis (DEA). Recent examples include the works of Blasco and Moya[29], Hernández et al. [30], Coll-Serrano and Blasco-Blasco [31], and Rodríguez and Echauri [32].

In this paper, we will use the Malmquist index (DEA-based technique), described in Färe et al. [33] and Coelli et al. [34]. The Malmquist Productivity Index (MPI) allows for changes in productivity estimates for individual wind farms between two time periods and breaks down the relevant changes into technological change and changes in technical efficiency. This index has the following advantages [35]:

- It is not necessary to establish prior assumptions about the behaviour of the unit being analyzed, such as cost minimization or profit maximization.
- It is based on distance functions so that the prices of inputs are not needed when it is being set up.
- It allows for the breakdown of certain elements that might help to explain the causes of changes in the production process.
- It allows the researcher to obtain different levels of results i.e. according to the economic unit or time period.

The MPI [33], under the output orientation[3], can be expressed in terms of a distance function (d) as equation (1) using the observations at time (t) and ($t+1$):

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[1][27] Contains a description of the different stages involved in the complex process of installing and bringing the wind farms online. For the economic and technical aspects of wind electricity generation, see [28].

[2]This database is published by Bureau Van Dijk. The financial information contained in this database comes from the balance sheets submitted by companies in the Commercial Registries. This database is a web tool that offers both general and company information relevant to more than 2.5 million Spanish and 800,000 Portuguese businesses. The utility of this database resides in the fact that it is one of the few sources which contains economic and financial information relevant to the developer companies that promote the given wind farms. Using this information, we have compiled a special index which we have called Input 1 (use of variable productive factors). The way in which this index has been compiled is explained in the final paragraph of this section (Methods and materials).

[3]The subscript "o" was introduced to remind us that these are output-oriented measures. Malmquist indexes of TFP input-orientated measures can also be defined in a similar way.

$$MPI_o(y_{t+1}, x_{t+1}, y_t, x_t) = \left[\frac{d_o^t(x_{t+1}, y_{t+1})}{d_o^t(x_t, y_t)} * \frac{d_o^{t+1}(x_{t+1}, y_{t+1})}{d_o^{t+1}(x_t, y_t)} \right]^{1/2} \quad (1)$$

This index measures the changes in the total productivity of the factors (TFPCH) and represents the productivity of the production point *(x_{t+1}, y_{t+1})* with respect to the production point *(x_t, y_t)*[4]. A value of MPI_o greater than 1 indicates growth in TFP, while a value of lower than1 identifies a decrease in this indicator.This index is the geometric mean of two indices; an index that uses the technology of period (*t*) and the other of period (*t +1*).

TheMPI formulation expressed in equation (1) can be broken down into two components: change in technical efficiency (close to the technological frontier) and technological change (variation in the border between the two periods),as expressed in equation (2).

$$MPI_o(y_{t+1}, x_{t+1}, y_t, x_t) = \frac{d_o^{t+1}(x_{t+1}, y_{t+1})}{d_o^t(x_t, y_t)} \left[\frac{d_o^t(x_{t+1}, y_{t+1})}{d_o^{t+1}(x_{t+1}, y_{t+1})} * \frac{d_o^t(x_t, y_t)}{d_o^{t+1}(x_t, y_t)} \right]^{1/2} \quad (2)$$

where the ratio outside the square brackets measures the change in technical efficiency (EFFCH). The terms inside the brackets are a measure of technical change (TECHCH). It is the geometric mean of the shift in technology between the two periods.

According to Farë et al. [33], one may calculate Malmquist productivity indexes relative to any type of technology. Equation (2) reflects the constant returns to scale (CRS) technology. If the distance functions under variable returns to scale (VRS) technology are also calculated, it becomes possible to breakdown the EFFCH term (efficiency change calculated under CRS) into pure efficiency change (PEFFCH) calculated under VRS and a residual scale change (SCH), a component which captures changes in the deviation between the VRS and CRS technology. Hence, the EFFCH term may be broken down according to equation (3):

$$EFFCH = PEFFCH * SCH = \left[\frac{d_o^{t+1}(x_{t+1}, y_{t+1})_{VRS}}{d_o^t(x_t, y_t)_{VRS}} \right] * \left[\frac{d_o^{t+1}(x_{t+1}, y_{t+1})_{CRS}}{d_o^{t+1}(x_{t+1}, y_{t+1})_{VRS}} \bigg/ \frac{d_o^t(x_t, y_t)_{CRS}}{d_o^t(x_t, y_t)_{VRS}} \right] \quad (3)$$

As a consequence, this methodology involves breaking down the changes in productivity into three main components (i.e., the change in pure technical efficiency, changes in scale efficiency and technological change):

$$TPFCH = PEFFCH * SCH * TECHCH \quad (4)$$

According to Ederer [36], from the empirical perspective, this breakdown procedure is relevant because it is important to measure not only the levels of inefficiency but also to investigate the sources of that inefficiency. To estimate the growth in productivity in period (t+1) relative to period (t), as reported in equation (4), it is necessary to estimate the six distance functions. This involves solving six

[4]The production point *(x_t, y_t)* for economic unity, represents the vector of outputs *(y_t)* which is obtained from the vector of inputs *(x_t)*.

linear programming problems for each wind farm. This programming is already incorporated in the various software packages that use DEA methodology. In this study, we used the Coelli DEAP program[37].

As stated above, in order to analyze the evolution of the productivity of the Spanish wind industry, we will use the SABI database. Specifically, we use the data registered at the close of the financial years 2007 to 2015. The record is made up of 96 wind farms whose main activity is described under heading 3518 of the National Classification of Economic Activities (CNAE-2009).

The 96 wind farms are located in four Spanish regions which, in combination, make up around 70% of the wind-generated power installed in Spain in 2016 (Table 3)[5].In order for the different accounting items on the wind farms' balance sheets to adequately represent the productive factors utilized in the generation of wind power and, in order to ensure that these factors could be compared across the whole range of wind farms, it was necessary to elaborate a special index; *use of variable productive factors* (which we have called Input 1). There appear to be no stable criteria in the database, either with respect to the chronology or among the parks themselves. Therefore, unit spending on personnel, the consumption of materials and other exploitation expenditure, with the financial costs included, were all used in order to elaborate an index that attempted to represent the utilization of all of the variable productive factors with the exception of capital. The capital input (Input2)[6], which may be considered to be a fixed or quasi-fixed factor of production is represented via *installed power* for each of the farms, using the information supplied by AEE[14].The output was represented using the income obtained from the exploitation of each of the wind farms during the reference year, and then deflated in line with the Electricity Price Index [38].

3. Results and discussion

Tables 4 and 5 contain the basic statistical information used in the productivity analysis for the 96 wind farms during the 2007-2015 period. Table 4 contains the descriptive statistics of the output and input variables. Table 5 contains the distribution of the 10 types of technology utilized in the modelling by region, and for the whole of the sample.

Table4
Descriptive statistics of the output and input variables.
Source: Own elaboration

	Output (Thousands of constant Euros)	Input1 (Factor usage index)	Input2 (Installed capacity in MW)
Mean	6444.617	156.0	25.4
Median	3335.163	97.8	24.0
Maximum	136983.0	7582.1	75.1
Minimum	6.347	1.4	0.9
Std. Dev.	1177.623	467.7	1.65
Observations	864	864	864

[5] Wind farms located in these regions were not considered, since they did not offer the minimal level of accounting information necessary in order to carry out the investigation.
[6] The capital factor is associated with the installed capacity of the farms, which is obtained as the product of the number of wind turbines multiplied by the nominal power of each.

Table 5
Distribution of technology by region and for the whole of the sample.
Source: Own elaboration

	Andalusia	Castile and León	Castile-la Mancha	Galicia	Total
Technology	***Number of parks (%)***	***Number of parks (%)***	***Number of parks (%)***	***Number of parks (%)***	***Number of parks (%)***
GAMESA	13 (46 .43)	13 (44 .83)	11 (50 .00)	1 (5 .88)	38 (39 .58)
VESTAS	5 (17 .86)	7 (24 .14)	4 (18 .18)	5 (29 .41)	21 (21 .88)
SIEMENS	1 (3 .57)	0 (0 .00)	0 (0 .00)	6 (35 .29)	7 (7 .29)
ALSTOM	0 (0 .00)	4 (13 .79)	1 (4 .55)	2 (11 .77)	7 (7 .29)
MADE	0 (0 .00)	2 (6 .90)	1 (4 .55)	3 (17 .65)	6 (6 .25)
SUZLON	4 (14 .29)	1 (3 .44)	0 (0 .00)	0 (0 .00)	5 (5 .21)
GE	0 (0 .00)	2 (6 .90)	3 (13 .64)	0 (0 .00)	5 (5 .21)
ACCIONA	2 (7 .14)	0 (0 .00)	2 (9 .08)	0 (0 .00)	4 (4 .17)
ENERCON	2 (7 .14)	0 (0 .00)	0 (0 .00)	0 (0 .00)	2 (2 .08)
DESA	1 (3 .57)	0 (0 .00)	0 (0 .00)	0 (0 .00)	1 (1 .04)
Total parks	28 (100)	29 (100)	22(100)	17 (100)	96 (100)

The analysis of the data presented in Table 4 shows that there is considerable variability among wind farms in Spain with respect to their level of inputs and the resultant outputs. The high level of variability occurs in a context in which production does not grow as illustrated in Figure 1. This great variability takes place in a context in which production does not grow as illustrated in Figure 1 With regard to the technology used by the farms (Table 5), the two predominant technologies are GAMESA (which represents nearly 40% of the total) and VESTAS (which represents practically 22%).However, in terms of the type of technology used,the region of Galicia is somewhat atypical in that more than 35% of the installed technology belongs to SIEMENS (technology that represents only 7% of the total).

The results of the modelling provide 10 indices for each of the 96 wind farms included in the sample. Given that this information is very extensive, it is provided in the Appendix. The appendix includes a table with the detailed results of the Malmquist productivity index (broken down into its components) for each of the 96 wind farms. These values are averages for the period 2007-2015. The results are presented for both of the models offered. Model A is estimated without modelling possible differences in the technology used for the generation of energy. Model B, on the other hand, explicitly takes into account the technology that each of the farms uses and models this as an additional input.A summary of these results by region is given in Table 6. The Malmquist index is given in the table and the values are shown in the two final columns(one for model A and another for model B). The index is the result of multiplying the columns that correspond to changes in technical efficiency by those that correspond to technological change. Similarly, the columns that correspond to changes in technical efficiency are the result of multiplying the columns that correspond to changes in pure technical efficiency by those that correspond to changes in scale efficiency.

Table 6
Malmquist indices, changes in technical efficiency and technological change for regions (geometric mean).
Source: Own elaboration

Region	Change in technical efficiency (EFFCH)		Technological change (TECHCH)		Breakdown of change in technical efficiency: Change in Pure technical efficiency (PEFFCH)		Change in scale efficiency (SCH)		Malmquist Index (TFPCH)	
	Model A	Model B	Model A	Model B	Model A	Model B	Model A	Model B	Model A	Model B
Andalusia	1 .118	1 .037	0 .934	1 .012	1 .194	1 .03	0 .937	1 .006	1 .044	1 .049
Castile and León	1 .103	1 .039	0 .926	0 .988	1 .184	1 .053	0 .931	0 .986	1 .021	1 .026
Castile-Mancha	1 .097	1 .02	0 .917	0 .975	1 .186	1 .052	0 .925	0 .969	1 .006	0 .994
Galicia	1 .172	1 .051	0 .934	0 .955	1 .217	1 .073	0 .963	0 .98	1 .094	1 .005
Mean (96)	1 .118	1 .036	0 .927	0 .986	1 .193	1 .05	0 .937	0 .987	1 .037	1 .022

The results of Table 6 clearly highlight the following:

- The inclusion of the different technologies in the modelling process is important given that, on assuming that all types of technology are similar (Model A), there is a tendency to overestimate the role of “changes in technical efficiency”, more specifically in the influence of “changes in pure technical efficiency” (PEFFCH) and, as a consequence, in the rise in the value obtained for the Malmquist Index (TFPCH).
- On differentiating between the types of technology that each wind farm uses (Model B), the “change in technical efficiency” (EFFCH) becomes less influential while technological change (TECHCH) becomes more important. As a consequence, there is more moderate growth in productivity, which is about 2% annually.
- Although the results of Model Bmodify those of Model A, the (TECHCH)component continues to negatively influence productivity growth. This indicates that the wind farms in question are failing to adequately take advantage of technological capacity in order to improve the levels of this indicator. This might be related to problems concerning connectivity, i.e. inefficiency or failures in connections between the wind farms and the national grid[9],which impedes the optimization of this output.
- Most noteworthy however, is that when the specific technological system used by each of the wind farms is included (Model B),there are important changes with respect to the relative growth in productivity across regions: while Castile-Mancharetains the last position in this particular ranking, Castile and Leon rises from third to second, Andalusia from the second to first and Galicia falls from first to third.

One possible explanation for these variations might be that in Model B, the different types or configurations of technology provide a range of productive capacities and that the regions might be using different sets of technological instruments. A comparison between Tables 5 and 7 would certainly seem to confirm this conclusion. Specifically, Andalusia moves into first place because more than 85% of its farms use technology which leads to above-average productivity growth rates(more than 14% of these farms use SUZLON technology which produces the greatest increases); Castile and Leon is the region that comes next (more than 72% of its farms use technologies that promote above-average growth), while Galicia, on the other hand, drops from first to third position in the ranking because only 35.3% of its farms use technology which produces above-average productivity (the most commonly used technology, used by more than 35% of farms is that of SIEMENS, which is one of the four worst in terms of productivity growth). These results are in agreement with those obtained by Iglesias et al. [27] and underline the relationship that exists between this type of wind turbine technology and technological progress.

Table 7
Results of productivity by type of technology.
(Mean values, Model B)
Source: Own elaboration

Technology	**Malmquist Index (tfpch)**
SUZLON	1 .142
GAMESA	1 .04
ACCIONA	1 .034
VESTAS	1 .028
Mean (96)	**1 .022**
MADE	1 .000
GE	0 .988
SIEMENS	0 .982
ENERCON	0 .961
ALSTOM	0 .935
DESA	0 .929

The results throw up another relevant question, namely why Galicia, which has the lowest percentage of farms using technologies with above-average productivity growth, does not occupy the last position in the former (Model B) ranking (rather than Castile-Mancha). One explanation might be that there is an appreciable difference between these two regions in terms of wind considered as a resource. In Spain, there are important spatial differences with respect to regions and the wind resources available[39]. According to Baskut et al. [40]the areas in which the wind is strongest and most constant are the preferred sites for wind farm installation.Similarly, Iglesias et al. [27]indicate that one of the most fundamental variables for analyzing the productive potential of a wind farm project in a given area is the existence of suitable wind patterns. In this sense, according to the work of IDAE [41], of the four regions analysed in this study (Table 8), Galicia has the greatest eolic potential in terms of average usable wind speeds and equivalent annual wind hours. The range of net equivalent hours is considered to be a good indicator of performance for wind farms. In addition, the information given in Table 8serves to explain the performance of the growth in productivity corresponding to the other three regions: Andalusia and Castile and Leon, which occupy the first two positions enjoy certain advantages in terms of technology and wind resources; Castile-Mancha occupies comes last since it has no competitive advantages in either of these two indicators.

Table 8
Wind resources measured in terms of wind speed and equivalent hours.
Source: IDAE [41]

Region	Average annual wind speed (m/s)*	Range of net equivalent hours (h)
Galicia	6.88	2300-2500
Andalusia	6.76	2200-2400
Castile and Leon	6.62	2100-2300
Castile-Mancha	6.38	1925-2125

(*) Usable wind resource (velocity>6metres/second, and up to 80 metros in height).

In addition to the differences that exist in productivity growth at a regional level, there are also important differences in the evolution of this indicator across the different years analyzed. Table 9 shows how the Malmquist productivity index evolves, i.e. it presents the changes from one year to the next. These values are averages for the 96 wind parks while considering the estimation of Model B. During the years 2008, 2010, 2013 and 2015 there are increases in productivity which are well above the average growth for the 2007-2015 period. However, it is likely that these annual differences are due to more than one factor. If the annual growth of TFPCHis compared to the growth in output for these 96 farms (Table 9 and Figure 1) it may be observed that, with the exception of 2013, the years in which there is growth in productivity there is also growth in output, and that the trend for both variables is similar (Figure 2), although the behaviour of output tends to be more stable.Therefore, given that wind energy production also depends upon the demand for energy at any given moment, this may explain why the demand variable is also conditioned by the annual results for the productivity of the group of wind farms analyzed in this study. The anomalous behaviour corresponding to 2013 (in which average productivity increases and average output decreases for the total of the 96 farms) is principally due to the fact that, during this year, although output falls, Input 1 (which takes in utilization index for the productive factor variables) falls to an even greater extent (while the capital input remains stable). This adjustment in the productive processes was probably caused, to a large extent, by the impact of the brusque regulatory changes introduced by the Spanish Government between the years 2012 and 2013[7]. These changes meant that the agents involved were obliged to restructure their operational strategies, thus significantly stalling the development of the sector [13].

Table 9
Malmquist indices, technical efficiency change and technological change for periods (geometric mean).
Source: Own elaboration

			Breakdown of change in technical efficiency		
Period	Change in technical efficiency (EFFCH)	Technological change (TECHCH)	Change in pure technical efficiency (PEFFCH)	Change in scale efficiency (SCH)	Malmquist Index (TFPCH)
	Model B	Model B	Model B	Model B	Model B
2007-08	1.209	0.976	1.442	0.838	1.181
2008-09	0.965	0.875	0.872	1.107	0.845
2009-10	1.022	1.179	1.013	1.008	1.205
2010-11	1.116	0.865	1.102	1.012	0.965
2011-12	0.992	0.995	1.020	0.973	0.987
2012-13	1.018	1.081	1.026	0.992	1.100

[7]Specifically, the Royal Decree-Law 1/2012 (27 January 2012), via which the financial stimulus package for the production of wind energy was eliminated, and the Royal Decree 9/2013 (12 July 2013), via which Spain retroactively changed the remuneration system for wind energy.

2013-14	0.985	0.803	0.999	0.985	0.791
2014-15	1.005	1.185	1.005	1.000	1.191
Mean	1.036	0.986	1.050	0.987	1.022

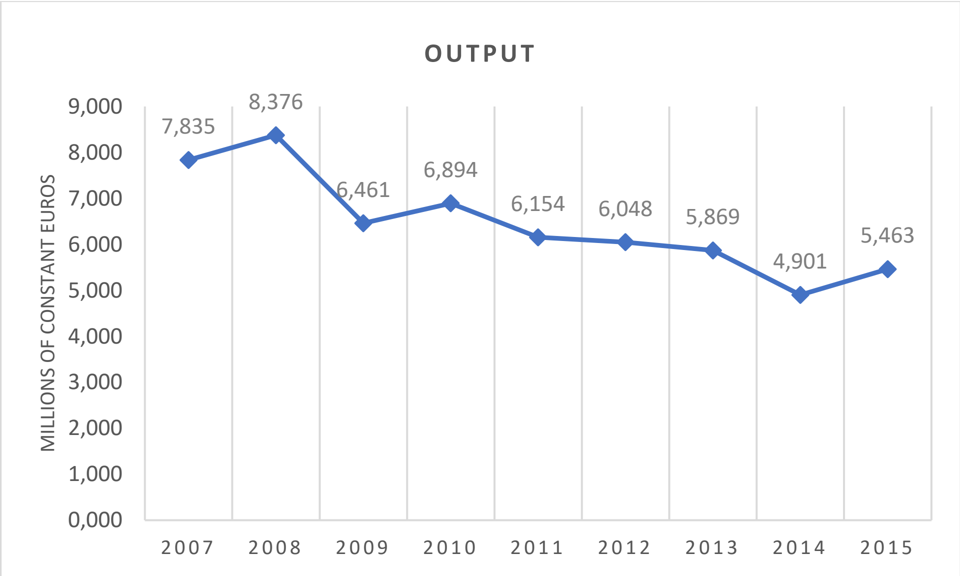

Figure 1. Temporal evolution of output (Annual means for the set of 96 wind farms).
Source: Own elaboration

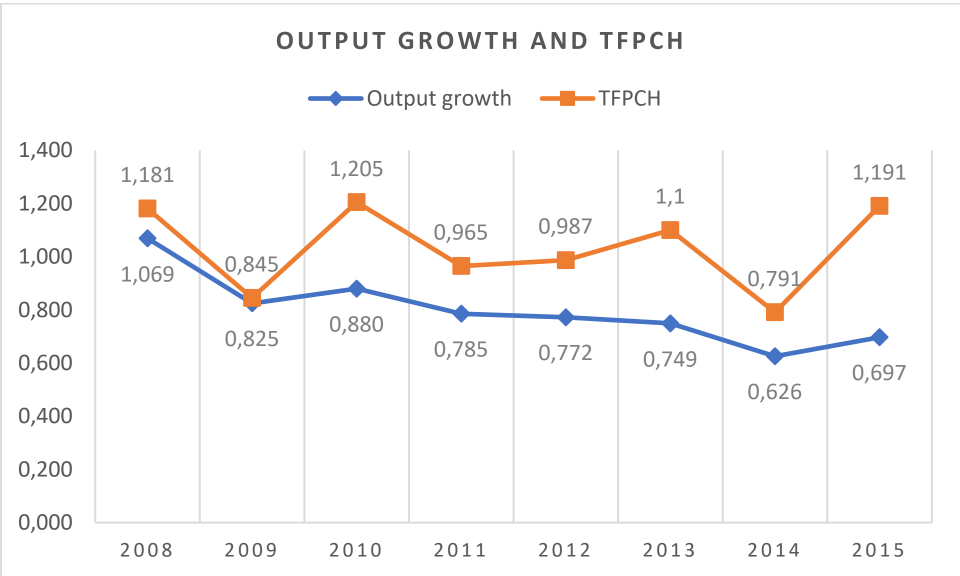

Figure 2. Growth in output and productivity
Source: Own elaboration

4. Conclusions and policy implications

The wind power industry is playing an increasingly crucial role throughout the world. It has evolved rapidly over recent years, but potential growth remains huge and this will have significant effects on the development of other renewable energies. In short, it will be a key element in the future sustainable energy mix, one which is less harmful to the environment. In spite of the negative impact of the systemic financial crisis on the financing of new eolic projects, the sector has continued to grow. In terms of installed capacity, wind energy, as a proportion of all renewable energies, has risen from 9.7% in 2007 to 23.7% in 2016. From a global perspective, China has played a leading role in recent years. In contrast, the development of the sector in Spain has been stymied by the lack of a coherent policy for wind power and other renewables, for which there has been no integral, coherent or stable regulatory framework.

In spite of the problems the Spanish wind power industry has experienced in recent years, it is currently the fifth biggest in the world in terms of wind installed capacity. In Spain, four regions (Andalusia, Castile and Leon, Castile-Mancha and Galicia) have driven the evolution of the eolic industry since 1995. In 2016, these four regions represented around 70% of the installed capacity for the whole of Spain. Nevertheless, although there is widespread agreement as to the importance of wind power within the energy mix, we were unable to find studies that analyzed the performance of total factor productivity (TFP) for Spanish wind farms.

This is a novel study, therefore, since it attempts to rectify this deficit by analyzing the evolution of TFP in the Spanish wind industry for the 96 wind farms located in the regions in which wind power plays an important role in the energy mix. The research makes use of the Malmquist productivity index (MPI), which allows us to carry out a breakdown of productivity performance for the main components (technological change, change in pure technical efficiency and in change in scale efficiency). In addition, the analysis is carried out by estimating alternative models, making it possible to highlight the role played by the different technologies used by the different farms. The flexibility of this methodology also means that it is possible to obtain results at the level of wind farm, type of technology, region and year.

By including technology as an additional input, it becomes possible to correct the estimations of the changes in productivity and its components. Once the estimations have been rectified by including the different types of technology utilized, the results indicate that the growth in productivity (an average of around 2% annually) is mainly due to a rise in the technical efficiency indicator (specifically in the component that reflects changes in pure technical efficiency). In contrast, the technological change component fails to contribute to growth in productivity, thus revealing that there is no optimization process with respect to technological capacity in most of the wind farms in the sample. This may be linked to the fact that output is adversely affected by connectivity problems between the farms and the national grid.

Additionally, when the model includes the technology used by each of the wind farms, it becomes possible to establish a ranking with respect to the average growth in productivity corresponding to each of the ten types of technology used. Given that the technologies might offer different productive capacities and that the different regions use different sets of technological instruments, the technology variable goes a long way to explaining the relative variations in productivity across regions. An overarching explanation of the relative positioning of each of the regions within the ranking is only possible by considering the role of wind-availability within each of these regions. Andalusia and Castile and Leon, which occupy the first positions in the ranking, have both advantages in terms of technology and in the availability of wind. Galicia, which occupies the third position, has a competitive advantage with respect to the availability of wind. Finally, Castile-Mancha comes last because it has no competitive advantages with respect to either of these two indicators.

In addition to the differences in productivity growth at a regional level, the results of the analysis also reveal the magnitude of the differences across time, from one year to the next, and these are even more significant. It seems highly likely that these annual differences in growth are due to a series of factors that together influence the performance in any given year. However, it also seems highly probable that there were two factors which were exogenous to the production process that played an important role in the results. These factors were; the demand for electricity that existed at each given time and the impact of the brusque regulatory change passed by the Spanish government between 2012 and 2013.

In light of these results, there should be new strategies better suited to optimizing the considerable economic and social potential available for wind power in Spain. The three main types of agents (social, economic and political) involved in the development of the industry must come together to harmonise the key factors necessary for creating a productive, more efficient process, namely; the importance of technology, the management of wind-availability and, the creation of a suitable regulatory framework. In consequence, the Spanish government should advocate and actively promote the growth of renewable energy sources and, in particular, wind power, not least because it must do so in order to comply with the climate-friendly energy objectives adopted by the EU. This policy should take the form of an integrated regulatory framework which is stable and facilitates the robust development of the industry, providing optimal access between wind farms and the Spanish national electricity grid.

The availability of wind must be considered must be weighed and included as a fundamental component of any strategy focusing on improved productivity. Therefore, prior to the installation of new wind farms, both local and regional entities in Spain (in accordance with their competencies) must take this variable into account. This factor, in combination with others, is crucial when it comes to organizing and managing their respective territories since the optimal zones or sites should be reserved for the creation of wind farms (eolic areas). Further, those who own land in these areas should take this factor into account in assessing the value of their property. Wind farm developers should take into account the localization of these areas, in addition to choosing the right type of technology for each farm, in order to ensure the optimal performance of their installations. Generating the right kind of technology for each eolic area should be a fundamental strategy for the firms that produce these kinds of technologies (technology suppliers).

Appendix

Malmquist indices, change in technical efficiency and technological change for each firm (geometric mean)

Source: Own elaboration

Firm	Change in technical efficiency (EFFCH)		Technological change (TECHCH)		Breakdown of change in technical efficiency: Change in pure technical efficiency (PEFFCH)		Breakdown of change in technical efficiency: Change in scale efficiency (SCH)		Malmquist Index (TFPCH)	
	Model A	Model B	Model A	Model B	Model A	Model B	Model A	Model B	Model A	Model B
1	1.24	1.13	0.93	1.07	1.39	1.07	0.89	1.06	1.15	1.20
2	0.96	1.02	0.97	1.00	1.17	1.02	0.83	1.00	0.93	1.01
3	1.18	1.04	0.96	1.06	1.20	1.05	0.99	0.99	1.13	1.11
4	1.21	1.00	0.94	0.96	1.23	1.00	0.98	1.00	1.14	0.96
5	1.07	0.94	0.95	1.03	1.07	0.94	1.00	1.00	1.02	0.97
6	1.01	0.96	0.94	0.99	1.10	0.96	0.92	1.00	0.96	0.95
7	1.19	1.10	0.95	1.01	1.26	1.10	0.95	1.00	1.14	1.12
8	1.21	1.06	0.95	1.08	1.22	1.06	0.99	1.00	1.15	1.15
9	1.05	1.01	0.94	1.00	1.23	1.01	0.86	1.00	0.99	1.01
10	1.05	0.94	0.94	1.01	1.10	0.94	0.96	1.00	0.99	0.95
11	1.01	1.00	0.95	1.06	1.23	1.00	0.82	1.00	0.96	1.06
12	1.31	1.12	0.88	1.07	1.38	1.00	0.95	1.12	1.15	1.20
13	1.08	1.00	0.96	1.03	1.10	1.01	0.98	0.99	1.03	1.03
14	1.06	1.00	0.95	0.97	1.07	1.00	0.98	1.00	1.00	0.97
15	1.46	1.34	0.99	1.07	1.54	1.35	0.95	1.00	1.44	1.44
16	1.12	1.00	0.94	1.03	1.16	1.00	0.96	1.00	1.05	1.03
17	1.14	1.00	0.93	1.03	1.14	1.00	1.00	1.00	1.06	1.03
18	1.19	1.24	0.82	0.96	1.40	1.21	0.85	1.02	0.97	1.19
19	1.14	1.23	0.95	0.98	1.41	1.23	0.81	1.00	1.08	1.20
20	1.00	0.90	0.93	0.99	1.03	0.90	0.97	1.00	0.93	0.89
21	1.20	0.99	0.81	0.99	1.00	1.00	1.20	0.99	0.97	0.97
22	1.25	1.12	0.93	1.07	1.38	1.08	0.90	1.04	1.16	1.19
23	0.99	0.94	0.94	1.00	1.10	0.94	0.91	1.00	0.94	0.94
24	0.98	1.03	0.94	1.00	1.17	1.03	0.84	1.00	0.92	1.03
25	1.14	1.03	0.95	1.01	1.18	1.03	0.97	1.00	1.08	1.04
26	1.05	1.00	0.94	1.00	1.16	1.00	0.90	1.00	0.99	1.00
27	1.04	1.00	0.93	0.93	1.04	1.00	1.00	1.00	0.97	0.93
28	1.14	1.02	0.95	1.00	1.17	1.02	0.98	1.00	1.08	1.01
29	1.17	0.99	0.93	1.03	1.19	1.31	0.98	0.75	1.09	1.01
30	1.13	0.99	0.93	1.02	1.14	1.02	1.00	0.98	1.05	1.01
31	1.12	1.00	0.95	0.99	1.14	1.00	0.98	1.00	1.06	0.99
32	1.02	0.92	0.95	1.05	1.07	0.92	0.95	1.00	0.97	0.97
33	1.08	1.00	0.93	1.03	1.22	1.00	0.89	1.00	1.01	1.03
34	1.02	0.95	0.94	1.02	1.11	0.95	0.92	1.00	0.96	0.96
35	0.98	0.95	0.94	1.02	1.09	0.95	0.90	1.00	0.92	0.97
36	1.07	0.94	0.85	0.98	1.10	0.94	0.98	1.00	0.91	0.92
37	1.06	0.94	0.95	1.05	1.06	1.00	1.00	0.94	1.01	0.99
38	1.18	1.03	0.82	0.98	1.21	1.03	0.98	1.00	0.97	1.01
39	1.22	1.06	0.80	0.98	1.25	1.06	0.98	1.00	0.98	1.04
40	1.52	1.67	0.96	0.98	1.91	1.67	0.79	1.00	1.45	1.63

41	1.13	1.00	0.94	1.02	1.14	1.00	0.98	1.00	1.06	1.02
42	1.11	0.88	0.89	0.94	2.16	1.17	0.51	0.75	0.99	0.82
43	1.01	0.97	0.94	0.99	1.11	0.97	0.91	1.00	0.95	0.96
44	1.00	1.00	0.86	0.87	1.00	1.00	1.00	1.00	0.86	0.87
45	0.97	0.97	0.95	0.89	1.00	0.97	0.97	1.00	0.92	0.86
46	1.06	1.01	0.92	1.01	1.16	1.01	0.92	1.00	0.98	1.02
47	1.05	1.15	0.95	0.81	1.08	1.15	0.97	1.00	0.99	0.93
48	1.08	1.17	0.95	0.81	1.10	1.17	0.98	1.00	1.02	0.95
49	1.14	1.04	0.95	1.06	1.15	1.07	0.99	0.97	1.09	1.10
50	1.16	1.01	0.88	1.00	1.19	1.01	0.97	1.00	1.01	1.01
51	1.14	0.99	0.81	0.94	1.23	1.00	0.92	0.99	0.92	0.92
52	1.24	1.01	0.99	1.06	1.25	1.01	0.99	1.00	1.24	1.07
53	1.26	1.30	0.92	1.01	1.52	1.30	0.83	1.00	1.16	1.31
54	1.06	1.20	0.94	0.81	1.12	1.20	0.94	1.00	1.00	0.97
55	1.24	1.10	0.95	1.06	1.31	1.17	0.94	0.94	1.17	1.16
56	0.92	0.80	0.87	1.00	0.94	0.80	0.98	1.00	0.80	0.79
57	1.11	0.96	0.87	1.01	1.14	1.00	0.98	0.96	0.97	0.96
58	1.07	0.95	0.98	1.05	1.08	0.95	1.00	1.00	1.06	1.00
59	1.04	1.03	0.95	0.96	1.14	1.03	0.92	1.00	0.99	0.98
60	1.26	1.27	0.79	0.97	1.46	1.27	0.86	1.00	0.99	1.24
61	0.99	0.93	0.94	1.03	1.07	0.93	0.92	1.00	0.93	0.96
62	1.12	1.01	0.95	0.92	1.12	1.01	1.00	1.00	1.06	0.94
63	1.11	1.04	0.98	1.04	1.12	1.08	0.99	0.97	1.09	1.08
64	1.17	0.99	0.83	0.99	1.19	0.99	0.99	1.00	0.98	0.98
65	1.01	0.97	0.95	1.01	1.12	0.97	0.90	1.00	0.96	0.97
66	1.01	0.97	0.91	1.00	1.11	0.97	0.92	1.00	0.92	0.97
67	1.03	0.98	0.95	0.99	1.12	0.98	0.92	1.00	0.98	0.97
68	1.05	0.96	0.95	0.99	1.10	0.96	0.95	1.00	0.99	0.95
69	1.25	1.57	0.80	0.80	1.48	1.57	0.85	1.00	1.01	1.26
70	1.12	1.01	0.99	1.03	1.14	1.01	0.98	1.00	1.11	1.05
71	0.98	1.08	0.95	0.93	1.17	1.08	0.83	1.00	0.93	1.00
72	1.33	1.21	0.97	1.03	1.55	1.48	0.86	0.82	1.28	1.25
73	1.13	1.03	0.95	0.99	1.18	1.03	0.96	1.00	1.07	1.02
74	1.13	1.03	0.98	1.04	1.15	1.03	0.98	1.00	1.11	1.07
75	1.08	1.00	0.94	1.02	1.16	1.00	0.94	1.00	1.02	1.02
76	1.13	1.00	0.95	1.07	1.24	1.00	0.91	1.00	1.07	1.07
77	1.06	0.97	0.94	1.01	1.13	0.97	0.93	1.00	0.99	0.98
78	1.10	1.01	0.96	1.03	1.10	1.05	0.99	0.96	1.05	1.04
79	0.97	1.02	0.97	0.93	1.12	1.02	0.87	1.00	0.94	0.95
80	1.11	1.06	0.97	1.02	1.11	1.13	1.00	0.94	1.07	1.08
81	1.17	1.00	0.95	0.98	1.18	1.00	0.99	1.00	1.11	0.98
82	1.15	1.00	1.03	1.03	1.15	1.00	1.00	1.00	1.18	1.03
83	1.23	0.99	0.84	1.01	1.23	1.00	1.00	0.99	1.04	1.00
84	1.15	0.94	0.94	0.91	1.21	0.98	0.95	0.96	1.08	0.86
85	1.24	1.13	0.99	0.87	1.25	1.31	0.99	0.87	1.22	0.98
86	1.64	1.31	0.80	0.98	1.64	1.00	1.00	1.31	1.32	1.28

87	1.08	0.98	0.99	0.94	1.08	0.98	1.00	1.00	1.07	0.93
88	1.24	1.05	0.98	0.88	1.28	1.25	0.96	0.84	1.20	0.92
89	1.09	1.00	1.01	0.98	1.09	1.00	1.00	1.00	1.11	0.98
90	1.27	1.11	0.83	0.98	1.30	1.11	0.98	1.00	1.05	1.09
91	1.25	1.02	0.93	0.92	1.37	1.00	0.91	1.02	1.16	0.94
92	1.12	1.14	0.94	0.89	1.15	1.14	0.98	1.00	1.06	1.01
93	1.05	1.03	1.01	0.86	1.10	1.03	0.95	1.00	1.06	0.88
94	0.91	0.94	0.96	0.98	1.10	0.94	0.83	1.00	0.88	0.93
95	1.10	0.98	0.96	1.04	1.10	1.20	1.00	0.82	1.05	1.02
96	1.28	1.28	0.80	1.01	1.49	1.28	0.86	1.00	1.03	1.29
Mean	1.12	1.04	0.93	0.99	1.19	1.05	0.94	0.99	1.04	1.02

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