



an open access  journal



Citation: Rodríguez-Navarro, A. & Brito, R. (2020). Might Europe one day again be a global scientific powerhouse? Analysis of ERC publications suggests it will not be possible without changes in research policy. *Quantitative Science Studies*, 1(2), 872–893. https://doi.org/10.1162/qss_a_00039

DOI:
https://doi.org/10.1162/qss_a_00039

Received: 23 October 2019
Accepted: 20 January 2020

Corresponding Author:
Alonso Rodríguez-Navarro
alonso.rodriguez@upm.es



Handling Editor:
Ludo Waltman

Copyright: © 2020 Alonso Rodríguez-Navarro and Ricardo Brito. Published under a Creative Commons Attribution 4.0 International (CC BY 4.0) license.



RESEARCH ARTICLE

Might Europe one day again be a global scientific powerhouse? Analysis of ERC publications suggests it will not be possible without changes in research policy

Alonso Rodríguez-Navarro^{1,2}  and Ricardo Brito¹ 

¹Departamento de Estructura de la Materia, Física Térmica y Electrónica y GISC, Universidad Complutense de Madrid, Plaza de las Ciencias 3, 28040, Madrid, Spain

²Departamento de Biotecnología-Biología Vegetal, Universidad Politécnica de Madrid, Avenida Puerta de Hierro 2, 28040, Madrid, Spain

Keywords: e_p index, European research, research assessment, research policy

ABSTRACT

Numerous EU documents praise the excellence of EU research without empirical evidence and in contradiction of academic studies. We investigated research performance in two fields of high socioeconomic importance, advanced technology and basic medical research, in two sets of European countries, Germany, France, Italy, and Spain (GFIS), and the UK, The Netherlands, and Switzerland (UKNCH). Despite their historical and geographical proximity, research performance in GFIS is much lower than in UKNCH, and well below the world average. Funding from the European Research Council (ERC) greatly improves performance in both GFIS and UKNCH, but ERC-GFIS publications are less cited than ERC-UKNCH publications. We conclude that research performance in GFIS and in other EU countries is intrinsically low, even in highly selected and generously funded projects. The technological and economic future of the EU depends on improving research, which requires structural changes in research policy within the EU, and in most EU countries.

1. INTRODUCTION

Currently, research is a key activity in all nations. This is widely recognized and highlighted by leading research journals, corporations, and government institutions. For example: “Scientific discoveries, new technologies, and the aggressive application of cutting edge knowledge are essential for success in a competitive global economy. As such, the strength of a country’s overall R&D enterprise—including both the public and private realms of this system—is an important marker of current and future national economic advantage.” (National Science Board, 2018, p. 4–7).

The EU is one of the strongest economies in the world, together with those of China and the USA. Considering the role that knowledge currently plays in an economy, to maintain this strong position, the EU must also hold a leading position in research. However, whether this occurs is a controversial matter, mainly due to the difficulties of assessing the real performance of a research system given the intangible nature of much of the output of research (Martin & Irvine, 1983).

In view of these considerations, this study aims to investigate EU research performance, especially considering the role of landmark publications, which comprise a small proportion of the total number of publications (Bornmann, Ye, & Ye, 2018). Furthermore, it focuses on two research fields of high socioeconomic importance: advanced technology and basic medical research (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b), and compares the performance of a small number of countries within the European Research Area (ERA) with excellent research indicators with that of others of lower performance. As a second tool, this study focuses on the research funded by the European Research Council (ERC), as a means to single out elite and generously funded research in high and low-performance countries.

1.1. Current Controversy About EU Research Performance

Since 2006, the research level in the EU has been controversial. While academic studies have demonstrated the weakness of European research (Albarrán, Crespo, et al., 2010; Bauwens, Mion, & Thisse, 2011; Bonaccorsi, 2007; Bonaccorsi, Cicero, et al., 2017; Dosi, Llerena, & Labini, 2006; Herranz & Ruiz-Castillo, 2013; Rodríguez-Navarro & Brito, 2018b; Rodríguez-Navarro & Narin, 2018), especially in fields that are at the forefront of technological knowledge (Bonaccorsi, 2007; Rodríguez-Navarro & Narin, 2018; Sachwald, 2015), the European Commission (EC) has developed research policies that assume that European research is excellent. For many years, EU research policy has been based on the “European paradox,” which proclaims strong research and weak innovation in the EU. Recently, references to this paradox have disappeared from EC documents, but the notion is as present as it was when it was defined (European Commission, 1995). For example, a report from an independent High Level Group appointed by the EC (European Commission, 2016) begins by describing EU research as in the European paradox: “When looking ahead to the future of Europe in a globalising world, the contrast is striking between Europe’s comparative advantage in producing knowledge and its comparative disadvantage in turning that knowledge into innovation and growth.” A subsequent report contains a motto: “Europe is a global scientific powerhouse” (European Commission, 2017b, p. 7).

Regrettably, the report of the High Level Group was the foundation for the preparation of the Horizon Europe research program for 2021–2027. Therefore, if the policy is not changed the new research program will be based on the notion that “Europe is a world leader in science” (European Commission, 2018a, p. 11), and that “In a swiftly changing world, Europe’s success increasingly depends on its ability to transform excellent scientific results into innovation that have a real beneficial impact” (European Commission, 2018d, p. 1). Press releases also suggest that the new research program will be based on a positive view of EU research, for example: “A new programme – Horizon Europe – will build on the achievements and success of the previous research and innovation programme (Horizon 2020) and keep the EU at the forefront of global research and innovation” (http://europa.eu/rapid/press-release_IP-18-4041_en.htm, accessed on March 7, 2019).

In contrast with this positive view of the EC, if the aforementioned academic studies are correct, EU research might remain below the level that the EU’s economy requires for many years. Considering the importance of research, this controversy about its level needs to be resolved as soon as possible. However, because the origin of the controversy lies in the lack of agreement on how to assess research performance, all efforts must be addressed to applying methods of research assessment that are convincing for all actors. This purpose, however, is more complex than it would be in a developing country, where simple indicators can be used.

The EU is a powerful economy, it was a world scientific leader not so long ago, it still produces an enormous amount of scientific research, and it has competitive industries that are able to maintain a high level of incremental innovation. EU research cannot, therefore, be correctly described using simple indicators that are unable to detect complex problems. For example, the statements: “The EU is a global research powerhouse responsible for one-fifth of all R&D investments worldwide” and “In terms of overall scientific production, Europe is in the lead, ahead of the United States and China” (European Commission, 2018e, pp. 78 and 154) are true, but these truths are not relevant. Investment and overall scientific production say nothing about discoveries and knowledge advancement, which are the driving force of technological advances and the roots of radical innovations.

1.2. EU Research Is Not Homogeneous Across Countries

Academic research assessments of individual countries have shown that the low performance reported for the EU as a whole does not occur in all EU countries; in fact, the UK and the Netherlands (in the EU) and Switzerland (in the ERA) maintain highly competitive research (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b).

These large differences across countries can lead to an incomplete perception of the situation of EU research if they are not taken into consideration; however, most of the studies that have so far examined EU research have considered the EU as a whole (e.g., Albarrán et al., 2010; Dosi et al., 2006; Herranz & Ruiz-Castillo, 2013; Rodríguez-Navarro & Narin, 2018), and this does not help to describe a problem that needs to be addressed at the country level. According to population, size, and degree of socioeconomic development, the set of countries that would have the greatest responsibility for weak research performance in the EU is Germany, France, Italy, and Spain (GFIS; see Table 2 in Bauwens et al., 2011; Tables 1 and 3 in Brito & Rodríguez-Navarro, 2018b; and Table 5 in Rodríguez-Navarro & Brito, 2018b). These countries represent approximately 50% of the EU population and 55% of its GNP, and, therefore, the study of these four countries, rather than the study of the whole EU, should give a clearer diagnosis of the difficulties of EU research in competing at the forefront of knowledge.

1.3. Research Assessment Methods

The controversial views regarding the level of research in the EU lie in the absence of agreement about how to measure success in research. Bibliometric indicators based on counting publications and citations have been used for a long time (Godin, 2003, 2006). However, if the purpose is to estimate the contribution to the advancement of knowledge then most of these indicators give misleading information. This occurs because only a low proportion of the total number of publications report important scientific breakthroughs, which is an extension of the differences that exist between “normal” and “revolutionary” science (Kuhn, 1970). This idea can also be deduced by taking into consideration that so far “the benefits of scientific discoveries have been heavy-tailed” (Press, 2013, p. 822). This implies that the evaluation of breakthroughs and publications in this heavy tail are of crucial importance in research assessment.

Counting the number of Nobel prizes has occasionally been used as a reliable indicator of research success (e.g., Braun, Szabadi-Peresztegi, & Kovács-Németh, 2003; Charlton, 2007a, 2007b; Heinze, Jappe, & Pithan, 2019; Schlagberger, Bornmann, & Bauer, 2016), but this method has serious limitations because Nobel prizes are awarded to extremely infrequent scientific achievements. It can therefore be applied to big science producers (e.g., the USA, the EU,

Massachusetts Institute of Technology [MIT], Harvard University, University of Cambridge) but in most countries and institutions it is a useless measure, because there are no Nobel prizes to be counted. Although Nobel prizes cannot be used as indicators of research performance, however, they can be used to validate other indicators, which demonstrates that many bibliometric indicators do not correlate with the number of Nobel prizes (Rodríguez-Navarro, 2011).

Accepting that what really counts in the progress of science are the infrequent scientific breakthroughs that cannot be counted in most countries and institutions, the conclusion is that research indicators cannot be formulated by simply counting something. Some dichotomous indicators count the number of papers in a certain fraction of the upper tail of citation distributions, assuming that these are the most influential papers (Albarrán, Herrero, et al., 2017). However, these indicators count a fraction of the upper tail that is too large and do not provide information about the number of less frequent papers that are really influential. For example, the number of papers in the top 1% ranked by citations does not provide information about the number of highly influential publications that are in the more exclusive top 0.02% (Bornmann et al., 2018).

The alternative to this type of indicator is to characterize the complete distribution of citations. Once the distribution is known, the probability of publishing highly cited papers at any level can be calculated (Rodríguez-Navarro & Brito, 2019). In Section 2.2 we describe the methods.

2. METHODS

2.1. Rationale and Design of This Study

As presented in Section 1.2, previous studies suggest that responsibility for the weak research performance in the EU lies mainly with GFIS; a study of these four countries as a single set has advantages in comparison to the study of independent countries, not only because the conclusions are more representative—GFIS represent around 50% of the EU's population—but, more importantly, because the study of a set of countries allows for a larger base of research publications, making it statistically more robust. According to previous studies in technological and biotechnological areas, and basic medical research, research performance in Germany is better than in France, Italy, and Spain; however, the differences are small when taking a competitive country, such as Switzerland, as a reference (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b). GFIS are thus more similar in their weakness, as compared to Switzerland, than different in their degrees of weakness.

The study of a single set of countries with weak research performances has, nonetheless, the inconvenience of lacking a reference of similar countries—in Europe—with competitive research performance. We therefore selected a reference set comprising the UK, the Netherlands, and Switzerland (henceforth UKNCH) for comparison in the analyses. The comparative research performances of UKNCH in fast-evolving technologies and basic medical research vary notably (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b) because university specialization in Europe (Bonaccorsi, Haddawy, et al., 2017) has a strong effect on small countries. Therefore, although UKNCH research performance is taken as a reference in this study, our results are not indicative of the research performances of the individual countries.

We studied domestic papers at the ERA level—that is, papers authored by at least one GFIS or UKNH researcher plus others from ERA countries external to GFIS and UKNCH, but none from nonERA countries. Therefore, collaborations of ERA countries external to GFIS and UKNCH could exist in any of the two sets of independent papers.

As already advanced in Section 1, another basic design of our study involves taking advantage of the EU funding programs, especially the ERC program, to select for different levels of excellence. The rationale is simple: The scientific success of a certain country or association of countries depends on a combination of the ability of its researchers, their funding resources, and the research environment—we use this term in a broad sense, including everything from stocks of knowledge to national evaluation methods (Sandström & van den Besselaar, 2018). By selecting a specific type of funding some of the country differences are eliminated and further insights are possible.

Statistically, citations follow a lognormal distribution (Rodríguez-Navarro & Brito, 2018a; Viuu, 2018; and references therein) where the μ and σ parameters of the lognormal function increase in parallel with research success. If a subpopulation in a given country is made up of the most capable researchers—for example, in an elite research university—it is certain that, *ceteris paribus*, the lognormal citation distribution of their publications will have higher μ and σ parameters than those of the total population. Because countries have complex research systems made up of multiple subpopulations of researchers, a low average capacity can be explained by (a) the low performance of all researchers due to a generally poor research environment and insufficient funding, and (b) the existence of many low research performance institutions that conceal the high performance of a few elite institutions.

These two possibilities can be distinguished by studying the ERC-funded GFIS and UKNCH publications. The ERC was created to promote excellence in science (Celis & Gago, 2014; Luukkonen, 2014), and it is based on generous funding and the selection of the most excellent research projects. Generous funding could correct insufficient funding in a country or set of countries, but not a poor research environment. It is therefore likely that studying the ERC-funded subpopulations will provide information about the research environment in GFIS and UKNCH.

ERC-funded GFIS research was also compared with the research of an elite institution. The ERC funding of research projects represents an *ex ante* selection that is significantly different from the selection of researchers in elite research institutions, whose members are mainly selected via an *ex post* research assessment improved by multiple considerations of future perspectives. The selected researchers then obtain generous funding. We studied the effect of these two models for selecting excellence by comparing MIT- and ERC-funded GFIS publications.

2.2. Research Assessment Approaches

The basis of this study was to calculate the probability that a random publication from a country or institution reaches a certain level of citations. For this purpose, most results were obtained through the use of the e_p index, which is based on analysis of the distribution of local publications among global publications (Rodríguez-Navarro & Brito, 2019). However, citation distributions are lognormal (Rodríguez-Navarro & Brito, 2018a; Viuu, 2018; and references therein) and local comparisons can also be performed by omitting the comparison with global publications through the more direct but less accurate method of comparing lognormal distributions of citations.

The first approach is based on the fact that considering their number of citations, the rank of local papers expressed as a function of their global rank follows a power law (Rodríguez-Navarro & Brito, 2018a). As a mathematical consequence, the distribution of local papers in global percentiles attending to their number of citations also follows a power law (Brito & Rodríguez-Navarro, 2018a).

The e_p index is a derivative of the exponent of the power law that percentile frequencies obey; that is, a mathematical parameter that characterizes the distribution of local papers

among the global papers. It reveals the *breakthrough potential* (Rodríguez-Navarro & Brito, 2018b), namely the efficiency of the system in scaling up from less cited papers to highly cited papers: For example, the decrease of the number of papers in the top 1% of most globally cited papers with reference to the number of papers in the top 10% of most globally cited papers. An e_p index of 0.1 indicates that as the percentile decreases, the number of papers in a country or institutions decreases at the same rate as in global publications. Therefore, if the e_p index is lower than 0.1 in a country or institution, the research performance of that country or institution is worse than the global average. Consequently, in countries that are international leaders in research, the e_p index must be significantly higher than 0.1—excellent research systems have e_p index values of around 0.2.

The probability that a random paper from a given country or institution reaches a top percentile x is calculated by simply raising e_p to a power, as shown by the formula (Rodríguez-Navarro & Brito, 2019):

$$P(x) = e_p^{(2 - \lg x)} \quad (1)$$

As a first approximation, it can be assumed that important breakthrough papers are linked to radical innovations and future technologies, while incremental innovations in present technologies are linked to less cited papers (Dewar & Dutton, 1986); therefore, a meaningful research assessment should also provide the probability and expected frequencies of these papers. The e_p index fulfills this condition because probabilities at all citation levels are powers of the e_p index; probabilities at high citation levels—infrequent achievements/high powers of the e_p index—correlate with the number of Nobel prizes (Brito & Rodríguez-Navarro, 2018a) and probabilities at low citation levels—more frequent achievements/low powers of the e_p index—correlate with peer reviews (Rodríguez-Navarro & Brito, 2020; Traag & Waltman, 2019).

In addition to this method, cross-country comparisons can also be performed by omitting the comparison with global publications through the more direct but less accurate method of comparing lognormal distributions of citations. In this method, once the parameters of the lognormal distributions of a country, institution, or subpopulation of papers have been calculated, the cumulative probability at any citation level can be calculated. In absolute terms, local probabilities do not have a clear meaning, but this meaning can be obtained through comparison with a reference or gold standard that publishes a similar number of papers. As already mentioned, MIT publications were used as a reference.

The formulas of the lognormal distribution and upper cumulative distribution for a paper to receive more than C_a citations are the following (Aitchison & Brown, 1963):

$$p(C, \mu, \sigma) = \frac{1}{\sqrt{2\pi}C\sigma} \exp\left[-\frac{(\ln C - \mu)^2}{2\sigma^2}\right] \quad (2)$$

$$p(C_a) = \int_{C_a}^{\infty} p(C, \mu, \sigma) dC \quad (3)$$

2.3. Technologies Selected in This Study

The EC reasonably places emphasis on the importance of research for the economic future of the EU. For example, one of the main features of the Horizon Europe research program is to “foster the EU’s industrial competitiveness and its innovation performance, notably supporting

market-creating innovation via the European Innovation Council and the European Institute of Innovation and Technology” (European Commission, 2018b).

The research areas and topics to be investigated were selected in two independent fields: physical and chemical technologies (henceforth TECH) and biological technologies and basic medical research (henceforth BIO-MED), which are currently at the forefront of knowledge. They were selected in two previous studies (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b), with a slight increase in the scope in the case of technology (see Section 2.5). These research areas and topics will probably continue being important and supporting market-creating innovations and healthcare advancements in the near and medium future.

2.4. Calculations of the e_p Index

As described in Section 2.2, the e_p index is a derivative of the exponent of the power law that percentile frequencies obey. For its calculation, we counted the number of papers from the two sets of countries and MIT that were in global top percentiles according to the number of citations, as described previously (Brito & Rodríguez-Navarro, 2018a; Rodríguez-Navarro & Brito, 2018b). In previous cases, we counted the number of papers in six top percentiles from 7 to 35, but for ERC publications we added top percentiles 3 and 1, because, in some cases, the percentile distribution of ERC publications deviates slightly from the power law. In these cases, the e_p index obtained from fitting the power law to the higher percentiles was higher than those obtained from fitting to the lower percentiles. When this occurs, to better predict the probability of breakthrough papers in the top 0.01%, we normally fitted the power law to the lower percentiles instead of fitting the power law to all data points. In the cases presented in this study the fits to the power law showed R^2 and p values calculated by using the χ^2 statistics (Press, Flannery, et al., 1989) that were higher than 0.99.

2.5. Bibliometric Searches

Bibliometric searches were performed in the Science Citation Index Expanded of the Web of Science Core Collection (WoS), using the “Advanced Search” feature. For TECH searches we used (TS=(ionic liquid* OR liquid electrolyte* OR liquid salt* OR energy transfer OR fuel cell* OR quantum dot* OR composite material* OR transistor* OR semiconductor OR superconductor OR graphene OR batter* OR solar cell* OR electronic OR metal organic framework* OR nano*) OR SU=Telecommunications)). For BIO-MED searches we used (SU=((biochemistry & molecular biology OR biotechnology & applied biotechnology OR cell biology OR microbiology) NOT (computer science OR mathematical & computational biology)) OR TS=((cancer OR crispr* OR microbiota OR stem cell* OR immunity OR inflamma*) NOT (statistics OR trial OR survey))). For ERC-funded publications we used FT=(ERC OR (European Research Council)); for EU-funded research excluding ERC- and Marie Curie (MC)- funded publications, we used FT=(((COST OR FEDER OR FP7 OR FP6 OR (European Social Fund) OR (European Regional Development Fund) OR (European Commission)) NOT (ERC OR (European Research Council) OR Marie Curie))). Although MC funding was excluded in these searches, MC publications were not treated as ERC publications because they have a lower level of excellence (results not shown).

We retrieved only “articles,” which excludes review papers, because review papers often receive more citations than the original articles on which they are based. Searches were performed between February 23 and March 5, 2019. Some countries or sets of countries were analyzed on different days, but each analysis on a different day was complete, including world

and country citation distributions. Because the ERC program started in 2007, our citation analyses were performed for the years 2011–2014.

To calculate the μ and σ parameters of lognormal distributions of citations of MIT and ERC-GFIS publications, we retrieved the number of citations of all publications and used the maximum likelihood method to fit the empirical data to a lognormal function.

3. RESULTS

3.1. General Appraisal of EU Research Performance

Before going into more detail, we obtained a general appraisal of the research performance in the EU from *Science & Engineering Indicators*, published by the National Science Board of the National Science Foundation (National Science Board, 2016, 2018). Among other indicators they report the proportions of papers within five citation-based global percentiles in 13 research areas for the years 2002, 2004, 2012, and 2014, which allow the calculation of the e_p index values. Although the maximum differences between USA and EU research occur in topics that are at the forefront of technological knowledge (Bonaccorsi, 2007; Rodríguez-Navarro & Narin, 2018; Sachwald, 2015), the National Science Board data enables a general appraisal of research performances in the EU and the USA. Table 1 records the e_p index values

Table 1. Values of the e_p index calculated from the data reported in *Science and Engineering Indicators*. Data for the years 2002 and 2012 are in the 2016 report, and data for the years 2004 and 2014 are in the 2018 report.

Research field	USA				EU			
	Year				Year			
	2002	2004	2012	2014	2002	2004	2012	2014
Engineering	0.126	0.138	0.133	0.134	0.096	0.105	0.109	0.102
Astronomy	0.127	0.119	0.125	0.132	0.102	0.109	0.109	0.107
Chemistry	0.134	0.131	0.127	0.114	0.093	0.093	0.093	0.091
Physics	0.128	0.134	0.145	0.143	0.102	0.099	0.113	0.116
Geosciences	0.118	0.119	0.131	0.130	0.095	0.103	0.109	0.111
Mathematics	0.121	0.126	0.109	0.112	0.091	0.096	0.095	0.106
Computer sciences	0.137	0.139	0.142	0.138	0.082	0.082	0.100	0.090
Agricultural sciences	0.129	0.118	0.127	0.128	0.100	0.106	0.118	0.112
Biological sciences	0.119	0.119	0.129	0.132	0.095	0.100	0.113	0.111
Medical sciences	0.127	0.126	0.132	0.135	0.096	0.100	0.117	0.118
Other life sciences	0.103	0.102	0.108	0.102	0.104	0.104	0.112	0.111
Psychology	0.115	0.111	0.121	0.110	0.084	0.102	0.096	0.105
Social sciences	0.120	0.119	0.118	0.119	0.083	0.094	0.100	0.107
Mean	0.123	0.123	0.127	0.125	0.094	0.100	0.106	0.107

Science and Engineering Indicators 2016 and 2018, National Science Board, National Science Foundation, Arlington, VA. Appendix Tables 5-59 and 5-48, respectively. In the e_p index, the higher the better.

in all these 52 cases—4 years and 13 research areas—which clearly indicate that while the USA is above the world average ($e_p \approx 0.12$) the EU is almost exactly at the world average ($e_p \approx 0.10$). Only in the case of “Other Life Sciences” was the EU slightly ahead of, or on par with, the USA.

In “Engineering,” the means of the e_p index values of the four evaluations are 0.13 for the USA and 0.10 for the EU. The top 0.01% of most cited papers reasonably represents the percentile where most breakthrough and landmark publications concentrate (Bornmann et al., 2018; Brito & Rodríguez-Navarro, 2018a), and the probability that a random paper is located in this percentile— e_p index raised to the fourth power, Eq. (1)—reveals the efficiency of research systems in making discoveries. The probability that a random paper reaches the 0.01 percentile in the field of “Engineering” is 2.9×10^{-4} in the USA and 1.0×10^{-4} in the EU, 2.9 times higher in the USA than in the EU. This is a significant difference that implies that the EU should publish 2.9 times more papers to obtain the same number of achievements.

The *Science & Engineering Indicators* reports have no data that allow a comparison of GFIS and UKNCH research. Therefore, we obtained a general overview of their differences by counting the number of universities among the top universities in the Leiden Ranking (Ranking, 2019). For this purpose, we counted the number of GFIS and UKNCH universities among the top 25, 50, and 100 universities ordered by the $P_{top\ 1\%}$ in the field of “Physical sciences and engineering,” in two periods, 2006–2009 and 2014–2017 (Table 2). The differences between UKNCH and GFIS were striking in the top 25, because in the two periods UKNCH had four and five universities while GFIS had none. In the top 50, UKNCH has eight and seven, and GFIS has three and zero universities in the two periods, respectively. In the top 100, again UKNCH performed better than GFIS. In the first period GFIS has 10 universities that decreased to only four in the second period. The differences between the two periods were due to the emergence of China as a global scientific powerhouse, which impaired the rank of GFIS universities the most, and had a lesser effect on UKNCH than on the US universities.

3.2. EU-Funded Publications in TECH and BIO-MED Research

This study focuses on TECH and BIO-MED; the number of papers published by GFIS and UKNCH in BIO-MED is rather high. In BIO-MED, it represents about 17–18% of the total number of publications; in TECH the proportion decreases to approximately 13% and 10% in GFIS and UKNCH, respectively (Table 3). These figures show that in addition to its economic importance, we are dealing with a paramount research activity in the investigated countries. The

Table 2. Number of universities among the top 25, 50, and 100 in the CWTS Leiden Ranking in periods 2006–2009 and 2014–2017 in the research field of “Physical sciences and engineering,” $P_{top\ 1\%}$ indicator

Country/Set	2006–2009			2014–2017		
	Top 25	Top 50	Top 100	Top 25	Top 50	Top 100
USA	17	28	45	11	20	31
UKNCH	4	8	17	5	7	11
GFIS	0	3	10	0	0	4
China	1	3	7	7	17	35

UKNCH: the UK, Netherlands, and Switzerland; GFIS: Germany, France, Italy, and Spain. Source: <https://www.leidenranking.com/ranking/2019/list>, accessed May 22, 2019.

Table 3. Total number of publications, and number of publications in chemical and physical technologies (TECH), and biotechnology and basic medical research (BIO-MED) from Germany, France, Italy, and Spain (GFIS), and from UK, Netherlands, and Switzerland (UKNCH)

Year	GFIS			UKNCH		
	Total	TECH	BIO-MED	Total	TECH	BIO-MED
2011	143,017	17,801	24,994	62,048	5,606	11,171
2014	149,224	20,080	26,828	63,066	6,250	10,884
2018	144,404	19,806	24,453	61,590	6,533	10,030

difference in the total number of papers between UKNCH and GFIS roughly reflects their population difference.

The data in Table 3 show a situation of concern for both UKNCH and GFIS, because the number of publications did not increase in the period from 2011 to 2018, when it is well known that several Asian countries were contributing to a notable increase in the number of publications and research advances in these technological areas (Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b; Rodríguez-Navarro & Narin, 2018). The consequence is that the share of global publications in TECH and BIO-MED has been continually decreasing from 2011 to 2018 in both GFIS and UKNCH. This loss of share is particularly important in TECH, but it also occurs for the USA.

Although this loss of share seems to be a general trend for the EU and the USA, it is especially worrying for GFIS because the e_p index values for TECH and BIO-MED publications (0.06–0.07) were significantly lower than the world average (Table 4). Taking these two facts together, the effect is that research by GFIS in technological areas and basic medicine could eventually become of low global relevance in terms of scientific advancement. Our next step was thus to study the reasons for this low research performance by analyzing the subpopulations of elite papers selected according to their funding sources.

The subpopulation of papers selected by their EU funding in programs other than ERC and MC was higher in GFIS than in UKNCH in the two technologies (Table 4; 14% versus 12% in

Table 4. Publications in TECH and BIO-MED from Germany, France, Italy, and Spain (GFIS) and from the UK, the Netherlands, and Switzerland (UKNCH): number and proportion of publications, and e_p index by type of funding (year 2014)

Country set/funding	TECH publications			BIO-MED publications		
	Number	%	e_p	Number	%	e_p
GFIS						
All papers published	20,080	100	0.062	26,828	100	0.066
EU funded not (ERC or MC)	2,813	14.0	0.066	2,305	8.6	0.075
ERC funded	726	3.6	0.143	510	1.9	0.166
UKNS						
All papers published	6,250	100	0.104	10,884	100	0.103
EU funded not (ERC or MC)	751	12.0	0.145	592	5.4	0.144
ERC funded	534	8.5	0.191	414	3.8	0.271

TECH, and 8.6% versus 5.4% in BIO-MED, for GFIS and UKNCH respectively). In GFIS, selection by this EU funding involved a weak increase in the e_p index, roughly 10%, with reference to that of the total number of papers. This indicates a practically nonexistent selection of above-average research in these programs. In contrast, this funding clearly increased the e_p index in UKNCH, from 0.10 to 0.14, which indicates a significant selection of above-average research.

The study of ERC-funded papers is more interesting, because ERC funding is based on the selection of the highest research excellence through high-quality peer review (Celis & Gago, 2014; Luukkonen, 2014). The proportion of this elite subpopulation (Table 4) was considerably lower in GFIS than in UKNCH—3.6% versus 8.5% and 1.9% versus 3.8% in TECH and BIO-MED, respectively—which once more denotes the lower research competitiveness of GFIS. Interestingly, despite the apparently more stringent selection by ERC funding in GFIS than in UKNCH, the e_p index had lower values for ERC-GFIS than for ERC-UKNCH papers: 0.14 and 0.17 versus 0.19 and 0.27 in TECH and BIO-MED, and GFIS and UKNCH, respectively.

This lower success of GFIS versus UKNCH in ERC-funded publications in TECH and BIO-MED is a general trend also seen in the number of ERC grants in all fields over the years (Figure 1). This number increased continually from 2007 to 2012, when it reached a plateau. Similarly, the number of ERC publications in TECH and BIO-MED increased from 2012 to 2016 and has remained almost constant since then (Figure 2). Interpretation of these data needs to consider that the size of the GFIS research system is more than twice that of the UKNCH system (Table 3).

3.3. Evolution of the ERC-GFIS, ERC-UKNCH, and MIT Publications

As already argued (Section 2.1), low e_p index values in a given country might arise in two different research scenarios: Publications are produced by either a homogeneous population of researchers of low competitiveness—most probably because of a poor research environment—or by a heterogeneous population of researchers, where some were highly competitive but others were less competitive. These two cases may be distinguished through the study of

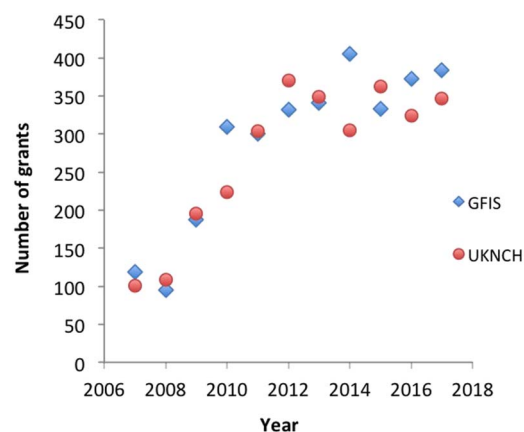


Figure 1. Number of grants from the European Research Council (ERC) awarded to Germany, France, Italy, and Spain (GFIS) and to the UK, the Netherlands, and Switzerland (UKNCH) from 2007 to 2017. Source: <https://erc.europa.eu/>, accessed 9 April 2019; Proof of Concept grants were not included.

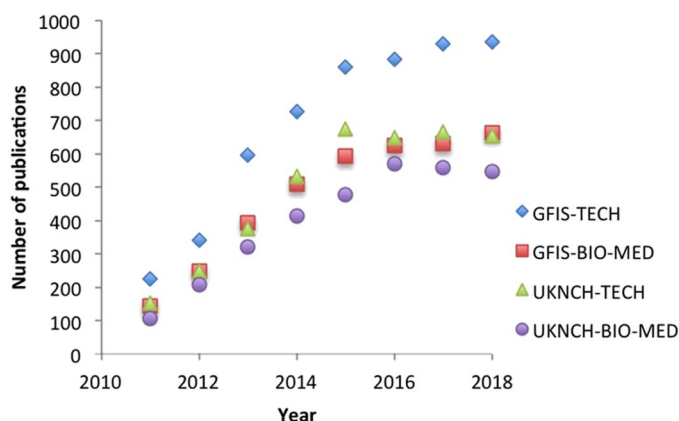


Figure 2. Number of ERC publications in rapid evolving physical and chemical rapidly evolving technologies (TECH) and in biotechnological and basic medical research (BIO-MED) from Germany, France, Italy, and Spain (GFIS), and from the UK, the Netherlands, and Switzerland (UKNCH) in years 2011–2018.

ERC-funded publications because ERC funding implies a selection for excellence. For better representativeness, the study must include several years, because the e_p index shows annual variations in the hot topics of this study.

Figure 3 shows the e_p index values for 2011–2014 for ERC-GFIS, ERC-UKNCH, and MIT publications in TECH and BIO-MED. In TECH there was no difference between ERC-UKNCH and MIT publications, while ERC-GFIS publications showed lower e_p index values. The e_p index in ERC-UKNCH and MIT publications varies around 0.2, while in ERC-GFIS publications it was around 0.15; the e_p index values for the three actors can be considered constant from 2011 to 2014. In BIO-MED, the e_p index values in ERC-UKNCH publications varies from 0.15 to 0.28, always below those of MIT, which varies from 0.23 to 0.33. In the case of GFIS the e_p index values varies around 0.15. In both ERC-UKNCH and MIT publications, there was a clear increase in the e_p index from 2011 to 2014, while it remained constant in the case of ERC-GFIS publications. Although irrelevant regarding the e_p index, it is worth noting that the

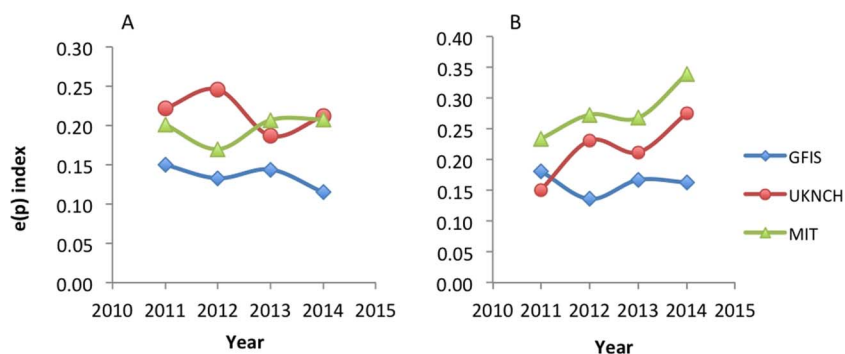


Figure 3. Values of the $e(p)$ index in years 2011–2014 of the ERC-funded publications from Germany, France, Italy, and Spain (GFIS) and the UK, the Netherlands, and Switzerland (UKNCH); and publications from the Massachusetts Institute of Technology (MIT). Physical and chemical technologies (TECH; left panel A) and biotechnology and basic medical research (BIO-MED; right panel B). Lines are drawn to guide the eye.

Table 5. Probability that a random ERC-GFIS or MIT paper is highly cited, calculated from the lognormal distribution of citations and from the e_p index; and MIT/ERC-GFIS probability ratio. The top 0.01 percentile was fixed for the e_p index method; for lognormal calculations, the number of citations was arbitrarily selected as described in the text

Year	Lognormal ERC-GFIS		Lognormal MIT		Citations	Lognormal probability		e_p probability top 0.01 percentile		MIT/ERC-GFIS Prob. ratio	
	μ	σ	μ	σ		ERC-GFIS	MIT	ERC-GFIS	MIT	e_p	Lognor.
TECH											
2011	3.458	1.196	3.420	1.339	1000	0.00195	0.00461	0.00051	0.00163	3.2	2.4
2012	3.240	1.118	3.412	1.191	850	0.00086	0.00257	0.00031	0.00084	2.7	3.0
2013	3.138	1.129	3.250	1.203	700	0.00126	0.00304	0.00043	0.00184	4.3	2.4
2014	2.922	1.062	3.028	1.196	500	0.00097	0.00385	0.00017	0.00187	10.7	4.0
BIO-MED											
2011	3.755	1.030	3.786	1.248	1000	0.00110	0.00617	0.00107	0.00300	2.8	5.6
2012	3.398	0.934	3.592	1.212	850	0.00017	0.00463	0.00034	0.00555	16.2	27.1
2013	3.325	1.068	3.566	1.290	700	0.00126	0.01036	0.00078	0.00516	6.6	8.3
2014	3.081	0.954	3.491	1.262	500	0.00051	0.01543	0.00071	0.01321	18.7	30.1

number of ERC-funded publications was continually increasing from 2011 to 2014 (Figure 2) while the MIT papers remained constant at around 550 (results not shown).

3.4. Calculations Based on the Lognormal Distributions: ERC-GFIS Versus MIT Publications

One way of comparing the research performances of two countries or institutions is to compare the probabilities of publishing highly cited papers. These probabilities can be calculated from the e_p index values Eq. (1) and from the their lognormal citation distributions Eq. (3). These two methods can be made equivalent, without any reference to the global papers, by selecting a number of citations for Eq. (3) that reasonably represent the highly cited tail that corresponds to the percentile used in Eq. (1). We used 1,000 citations for papers published in 2011 and reduced the numbers in proportion to the lower citation window for papers published in 2012–2014.

Table 5 summarizes the MIT and ERC-GFIS probabilities and their ratios calculated following both approaches—Eq. (1) and Eq. (3). The results could not be equal because there was not an exact equivalence between the 0.01 percentile applying the e_p index method and the number of citations reasonably but arbitrarily selected for the lognormal calculation. Nonetheless, the results are totally consistent and exhibit similar annual variations; they unequivocally show that ERC-GFIS research does not compete well with MIT research in TECH and BIO-MED.

4. DISCUSSION

4.1. Wrong Diagnoses and Misguided Policies

This was the title of the final section and conclusion of a paper about European research that was written 13 years ago (Dosi et al., 2006). There have been some changes since then, especially regarding basic research and the creation of the ERC, but essentially the situation

has not altered. The EC brags about excellent research in contradiction to academic studies (Section 1); the question is whether this excellence is a misjudgment based on incorrect assessments.

As a first approach to evaluate European research, we took advantage of the large amount of data provided by two successive reports of the *Science & Engineering Indicators* (National Science Board, 2016, 2018). The advantage of using these data is that they have been generated by the USA's National Science Board and not by EU academics. The data recorded by the *Science & Engineering Indicators* include the distribution of papers in 13 research areas and five percentiles for four years across a span of 13 years from 2002 to 2014.

As discussed in Section 3.1, according to the e_p index values (Table 1), the advantage of the USA over the EU is high. Only in the case of "Other Life Sciences" was the EU slightly ahead of, or on par with, the USA. The top 0.01% of most cited papers reasonably represents the percentile where most breakthrough and landmark publications concentrate (Bornmann et al., 2018; Brito & Rodríguez-Navarro, 2018a). In "Engineering," the probability that a random paper locates in this percentile is 2.9 times higher for a US paper than for an EU paper.

It is worth highlighting that the engineering research field mixes different technologies and that the 2.9 times difference is just the tip of the iceberg. In rapidly evolving technology topics, in the EU excluding the UK, the difference can be up to eight times (Rodríguez-Navarro & Brito, 2018b). The question raised by these results is whether the EU, excluding the UK, is prepared to invest eight times more in research than the USA to obtain a similar number of scientific advances.

In summary, academic publications and simple analyses (Table 1) show that the EU is not a global scientific powerhouse. If current research policy continues to be based on the same wrong diagnoses of scientific excellence that have oriented EU research policy for more than 20 years, then EU research will not correct its weak position. Even worse, the EU had only two relevant competitors 20 years ago (the USA and Japan), but China (together with other Asian countries) is currently in the competition and becoming even stronger than the USA and Japan.

The EU's sustained praise of its research excellence based on wrong diagnoses gives rise to misguided research policies and failures in reaching predicted targets. For example, the objective of the Lisbon Strategy, launched in 2000, that the EU should become "the most competitive knowledge based economy in the world by 2010" (European Commission, 2010, p. 2), was far from being achieved.

4.2. Research in the EU Is Heterogeneous

The EU is not a homogeneous set of countries as regards research (Bauwens et al., 2011; Leydesdorff, Wagner, & Bornmann, 2014); some countries are more efficient and some less efficient than the global average. As shown in previous studies (Bauwens et al., 2011; Brito & Rodríguez-Navarro, 2018b; Rodríguez-Navarro & Brito, 2018b) UKNCH represent the efficient countries while GFIS represent the less efficient countries; according to empirical evidence, the addition to GFIS of Poland, Romania, Greece, Czech Republic, Portugal, Hungary, Bulgaria, Serbia, or a few other countries would increase the size of the set without improving the research efficiency of GFIS. A comparison of GFIS and UKNCH thus provides a reliable picture of the heterogeneity of EU research and of its weakness in most of the EU countries. It must be taken into account for this comparison that the GFIS research system is more than twice the size of that of UKNCH (Table 3).

The reports of the USA's National Science Board, which we used as a first approach to characterize EU research, do not include data that allow a comparison of GFIS and UKNCH research, but an overview of their differences can be obtained by counting the number of universities among the top global universities with the highest $P_{\text{top } 1\%}$ indicators in the Leiden Ranking (Table 2). The results show unequivocally the low research level of GFIS with reference to UKNCH and the USA. If GFIS had the same level as UKNCH, the EU would probably be ahead of the USA in research.

4.3. Research in TECH and BIO-MED

Although research in many different fields is important for humanity, the knowledge-based economy includes a more limited number of research fields. TECH and BIO-MED are representative samples of these fields. As mentioned above, research performance in GFIS reasonably represents the average research performance of the whole EU. The low values of the e_p index of GFIS in these specific fields (≈ 0.06 ; Table 4) therefore reveals that the research performance of the EU in the areas that support the knowledge-based economy is worse than in broader scientific areas (e_p index ≈ 0.1 ; Table 1).

This scenario is absolutely baffling. It is startling that some of the EU's weakest research is precisely in the research fields that are crucial for the economy. Many EC documents praise EU achievements in many different fields, such as cancer treatments, solar jet fuel, never-ending batteries, exploring the universe, and so on (European Commission, 2018c). These achievements are absolutely real; we have already noted that EU research is the research of a powerful economy (Section 1.1). The important question is therefore whether the number of such achievements is in tune with the size of the EU economy. Assuming that the USA and the EU are of similar sizes in terms of GDP, all the data indicate that the number of important EU achievements in research is potentially six to eight times lower than it should be.

In summary, it is true that the EU is "responsible for one-fifth of all R&D investment worldwide" (European Commission, 2018e, p. 78), and that it produces a certain number of notable achievements in technology and medicine (European Commission, 2018c), but the number of research achievements in the EU is lower than in the USA and probably insufficient to maintain a competitive knowledge-based economy.

4.4. Research Assessments by Elite Samples of Publications in TECH and BIO-MED

To further investigate the differences between GFIS and UKNCH in TECH and BIO-MED we focused on elite research publications.

In Section 3.3 we considered that there are two potential reasons for the low GFIS values of the e_p index in TECH and BIO-MED (Table 4): (a) a generally weak performance due to a poor research environment, and (b) a small, highly competitive population of researchers mixed with a large less competitive population; these two causes cannot be distinguished by studying the whole production in these research areas. Therefore, we focused on an elite sample of ERC publications. ERC grantees are selected through a rigorous peer-review process that considers both the excellence of the project and the previous scientific success of the applicants (Celis & Gago, 2014; Luukkonen, 2014); for the EC, the ERC, "in just a few years, has become the point of reference for excellent frontier research in Europe" (European Commission, 2017a, p. 27). Our data indicate that there are excellent ERC publications, but their frequency is not the same in all EU countries. The first difference we noticed between GFIS and UKNCH in the two research areas under study, TECH and BIO-MED, was in the proportion of ERC versus the total

number of publications. This proportion in GFIS (3.6% in TECH and 1.9% in BIO-MED) was lower than in UKNCH (8.5% in TECH; 3.8% in BIO-MED), which suggested higher success of UKNCH in obtaining ERC grants.

The inference that a lower proportion of ERC publications in TECH and BIO-MED reveals less success in obtaining ERC grants cannot be checked in terms of grants in these research areas, because those grants cannot be distinguished and counted. However, in the whole ERC program, different levels of success in different countries can be checked by comparing the total numbers of ERC grants. Although the annual number of ERC grants awarded to GFIS and UKNCH increased more than threefold in the 2007–2018 period, the ratio between GFIS and UKNCH grants remained almost constant over this period (Figure 1). Considering that the size of the GFIS research system is twice that of UKNCH (Table 3), the success of GFIS in terms of ERC grants is about half that of UKNCH.

The lower success of GFIS in terms of ERC grants may be due to either a lower proportion of applications or a higher number of rejections. We cannot distinguish between these two possibilities with our data, but the former seems unlikely because in less stringent EU-funded programs GFIS is more successful than UKNCH. The ratio between GFIS and UKNCH publications in EU-funded publications in TECH and BIO-MED, excluding ERC and MC publications, is thus around 3.8 (Table 4), which is higher than the GFIS/UKNCH ratio considering the total number of publications (3.2 in TECH and 2.4 in BIO-MED). In contrast, the equivalent ratio in ERC-GFIS/ERC-UKNCH publications is 1.3. In other words, in the less stringent EU funding programs GFIS are more successful than UKNCH, whereas in the stringent ERC funding program the opposite is true. It is unlikely, therefore, that the lower success of GFIS in the ERC funding program is due to there being less interest; the higher success of UKNCH versus GFIS in the ERC program probably reflects the higher research competence of UKNCH.

Figure 3 shows the values of the e_p index throughout four years, further demonstrating that the excellence of ERC publications is lower in GFIS than in UKNCH—the means of the e_p index value in GFIS (0.14 in TECH and 0.16 in BIO-MED) were lower than in UKNCH (0.22 in both TECH and BIO-MED). This is an important conclusion, because ERC publications should be at the same level in GFIS and UKNCH—we assume that the selection procedure for grantees is the same for all countries. In other words, the excellence of grantees and projects is similar in GFIS and UKNCH, but the execution of the projects is less successful in GFIS than in UKNCH. We also used MIT publications as an external standard for the comparison of ERC publications (Figure 3), and the superiority of MIT publications over ERC-GFIS publications is beyond doubt.

Taken together, in terms of breakthrough frequencies, our results reveal the high level of excellence of the ERC-funded GFIS research. As indicated above, the probability of achieving important breakthroughs equals the e_p index raised to the fourth power, and a similar probability can also be calculated from the lognormal distributions of citations by fixing a certain high level of citations (Section 3.4). Global publications are ignored in the latter approach, which implies that the two calculations are independent—although they are conceptually equivalent and mathematically dependent (Rodríguez-Navarro & Brito, 2019). Table 5 shows that both methods lead to the same conclusion, that of a limited research excellence of ERC-GFIS publications; the coherence of the results strongly supports that there is no flaw in the methods employed.

In summary, GFIS shows lower competence than UKNCH at obtaining ERC grants, and GFIS-ERC publications have a lower probability than UKNCH-ERC and MIT publications of reporting breakthroughs.

4.5. Research Environment Conditions Research Performance

Both MIT and ERC publications are elite samples from the total number of publications in TECH and BIO-MED, but originated from two completely different procedures for selecting researchers. MIT and all other elite research institutions attract the brightest researchers because these institutions offer a superb research environment. Once in the institution, these researchers can freely apply for competitive research funding without any specific internal requirements.

The process is completely different in the case of ERC funding. Any researcher from any ERA institution can apply. Only the past scientific performance of the applicant and the content of the project are considered for the selection. No GFIS university is among the top 25 in the CWTS Leiden ranking and there are few among the top 100 (Table 2), which implies that a certain number of ERC grantees can be in universities that do not provide a research environment that is at the expected ERC level. In many of these cases, ERC grantees will have to attend to many hours of teaching and bureaucracy and, at the same time, grantees and hired postdocs will be under great publish-or-perish pressure, which increases the quantity but not the quality of publications. In this research environment the productivity at the forefront of knowledge will be lower for ERC-GFIS grantees than for the MIT researchers. In our opinion this explains why ERC-GFIS publications have a lower likelihood of reporting a scientific breakthrough than MIT publications (Figure 3; Table 5). Again, the same conclusion is obtained by comparing ERC-GFIS and ERC-UKNCH publications: Equivalent ERC-funded projects have a lower probability of success if executed in GFIS rather than in UKNCH.

The number of ERC-GFIS publications is only 2–4% of the total number of GFIS publications in TECH and BIO-MED (Table 4). If the ERC-GFIS researchers do not compete well at the forefront of knowledge after this stringent selection, it can only be because the whole research system is not competitive, and other GFIS researchers will probably be even less competitive. This explains why the e_p index of the publications of the whole population of GFIS researchers in TECH and BIO-MED is only 0.06 (Table 4), well below the world average.

4.6. Incremental Versus Radical Innovations

Our study is about research; questions about innovation must be treated through specific approaches (as in e.g., Archibugi & Filippetti, 2011; Filippetti & Archibugi, 2011). However, it is well established that innovation depends on scientific research (Jonkers & Sachwald, 2018) and that “although a high level of efficiency can be achieved with incremental innovation performance, radical innovation performance is needed to avoid generating competence traps” (Forés & Camison, 2015, p. 831).

It is worth noting that ERC-funded research is addressed to produce breakthrough papers and that many of the top 0.01% of the globally most cited papers report breakthrough achievements. These achievements are basic for radical innovations—innovations that contain a high degree of knowledge. However, a large fraction of all technological progress lies in incremental innovations—innovations that contain a low degree of knowledge (Dewar & Dutton, 1986). This type of innovation depends on external absorption and the internal creation of a type of research that might not be highly cited and that is unlikely to be ERC funded. GFIS, and especially Germany and France, probably compete better in this type of research (Tijssen & Winnink, 2018) than at the forefront of knowledge. This possibility, however, should not conceal the undesirable consequences of performing research with low e_p index values. First, because a low e_p index affects the performance of the whole research system and is not linked

to any specific citation level, which includes the low-cited papers that support incremental innovations; and second, because present scientific breakthroughs at the forefront of knowledge are the basis for technology that will be common in the midterm future. Present-day low numbers of research breakthroughs will thus become future technological dependences.

4.7. Might the Weakness of EU Technological Research Be Corrected?

We have already explained that the goal of the EU becoming the most competitive knowledge-based economy in the world by 2010 was not achieved. China's scientific production is growing rapidly (Fu & Ho, 2013; Leydesdorff et al., 2014) and might reach this target in the near future because China is developing a strong research system (Liu, Serger, et al., 2017), especially in fast-evolving technologies (Kostoff, Briggs, et al., 2007; Rodríguez-Navarro & Narin, 2018). Copying China's strategy might be effective in the EU and it is worth noting that China has been developing its research system *de novo*, which is not the case for many EU countries. The EU's problem with research is probably thus a problem of research policy. The lower success of Germany or France versus UK in Nobel prize awards (Gros, 2018) or number of highly cited researchers (Bauwens et al., 2011) does not have any other explanation. If GFIS were to copy UKNCH research policies then they should achieve a similar success in research.

The low levels of investment of some EU countries in research (European Commission, 2010, p. 9) suggest that the governments of some EU countries are not convinced about the economic benefits of research. This is confirmed in Spain, where the drastic cuts (Pain, 2012) that are leading to the dismantling of the research system suggest that Spanish governments see research as a dispensable social activity (Rodríguez-Navarro & Narin, 2018). The problem is not only investment, however, because the UK and the Netherlands invest less in research than Germany and France (European Commission, 2010, p. 9), but achieve a much higher probability that a random paper will reach the 0.01 percentile (the probability is obtained by dividing the $P_{\text{top}0.01\%}$ indicator by the number of papers or using the e_p index and Eq. (1), for example with data in Table 5 in Rodríguez-Navarro and Brito [2018b]).

In some countries, independently of other internal constraints, the repeatedly acclaimed and long-lasting notion of EU research excellence backed by the EC and the High Level Group mentioned in Section 1 might lead to a belief that it is not necessary to increase research. The consequences of this scenario are important because around 85% of EU public investments in research and innovation come from national funding (European Commission, 2018a) and the EU "does not wish to usurp national authorities in the management and implementation of these activities"—the subsidiarity principle (European Parliament, 2017, p. 10). A necessary first step for the EU in order to return to being a global scientific powerhouse is to recognize its research weakness. In addition, the EC should warn the less competitive countries of their low-efficiency research and eventually penalize this lack of solidarity. Taking the EU's Stability and Growth Pact (https://ec.europa.eu/eurostat/statistics-explained/index.php/Government_finance_statistics, accessed April 30, 2019), as a model, a minimal investment in research could be imposed on all EU member states. In contrast, it would be difficult for the EC to impose a general research policy.

The reasons for research weakness might be different in each country, because success depends on several key prerequisites being fulfilled (Bornmann & Marx, 2012), which implies that unsuccessful research across countries can have multiple causes. This would explain why two countries that are so different in technological research, Germany and Spain, are similarly distant from Switzerland in terms of the e_p index (Rodríguez-Navarro & Brito,

2018b). In Germany, governments are interested in research and fund it generously (Federal Ministry of Education and Research, 2018). In contrast, the Spanish government's drastic cuts to research funding (Pain, 2012) show that it considers research to be a dispensable activity. The answer to the question of why the German and Spanish e_p index values in technological research are, nonetheless, not too dissimilar might shed light on the general problems of GFIS regarding excellence in research.

A likely possibility is that the difficulties that GFIS researchers experience in carrying out competitive research might be related to their universities (Bauwens et al., 2011). In most advanced countries universities play a decisive role in national research and there might be a causal relationship between weak research and the absence of universities in top positions in the Leiden Ranking. Although this causal relationship has yet to be specifically studied, it is clear that some types of university governance might be determinants of low research performance (Aghion, Dewatripont, et al., 2008). For example, a high degree of cronyism and an institutional culture that does not favor competition, creativity, intellectual risk, and openness to the outside world impair research performance (Rodríguez-Navarro, 2009). University governances are different across countries (Paradeise, Reale, et al., 2009) and general recommendations for improvements (CREST Fourth OMC Working Group, 2009) might be of little help. Each country should take care of its own university system, but the results should be controlled by the EC, as in the EU's Stability and Growth Pact. If the EU genuinely wants to recover its past status as a global scientific powerhouse and to maintain a competitive, knowledge-based economy in the near future, then strict measures should be taken by all EU countries regarding research. While increasing research investment is necessary (Pavitt, 2000), it is not sufficient to improve research; unrealistic declarations of excellence will certainly delay improvements.

5. CONCLUSIONS

Our study distinguishes research success between the more competitive (UKNCH) and less competitive (GFIS) countries. It is surprising that among advanced countries as physically close as the Netherlands, Switzerland, Germany, and France, it is the Netherlands and Switzerland that are highly competitive, while Germany and France are much less competitive at the forefront of technological knowledge. The primary purpose of EU research policy should be to correct the deficient research performance observed in GFIS and in many other EU countries. The EU would be a global scientific powerhouse if most of its countries were as efficient as UKNCH are.

The finding that the probability that a random ERC publication reports a breakthrough is higher in UKNCH than in GFIS clearly suggests that the weakness of GFIS research is not just a problem of funding for research projects. Our results support that similarly ERC-funded projects are more successful if they are executed in UKNCH rather than in GFIS. Therefore, although an increase in investment is necessary, the EU will not improve its research performance by exclusively increasing investment and expanding the ERC program. Improvement of the observed low research success by most EU member states requires political measures.

In this scenario, the repeated assertion that EU research is excellent operates against the solution of the problem. The conviction of governments that the science performed in their countries is excellent demotivates them from investing more in research and from making reforms that are necessary but unpopular. The failure of the strategic goal of the Lisbon European Council in 2000 of the EU becoming the most competitive knowledge-based economy by 2010 is a lesson that should be learned.

The EU's Stability and Growth Pact only includes financial rules, without considering that economic growth also depends on the generation of knowledge. The future of the EU will not be ensured by the sole application of financial rules.

ACKNOWLEDGMENTS

We thank Juan Imperial and Manuel Pérez-Yruela for insightful and constructive feedback. We also thank two anonymous reviewers for their helpful suggestions on improving the original manuscript.

AUTHOR CONTRIBUTIONS

Alonso Rodríguez-Navarro: Conceptualization, Data curation, Formal analysis, Investigation, Supervision, Visualization, Writing—original draft, Writing—review & editing. Ricardo Brito: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, visualization, Writing—review & editing.

COMPETING INTERESTS

The authors declare that there are no competing interests.

FUNDING INFORMATION

This work was supported by the Spanish Ministerio de Economía y Competitividad, Grant Number FIS2017-83709-R.

DATA AVAILABILITY

The raw bibliometric data were obtained from Clarivate Analytics' Web of Science database. A license is required to access the Web of Science database.

REFERENCES

- Aghion, P., Dewatripont, M., Hoxby, C., Mas-Colell, A., & Sapir, A. (2008). The governance and performance of universities: Evidence from Europe and the US. *Economic Policy*, 25, 7–59.
- Aitchison, J., & Brown, J. A. C. (1963). *The Lognormal Distribution – with Special Reference to its Uses in Economics*. Cambridge: Cambridge University Press.
- Albarrán, P., Crespo, J. A., Ortuño, I., & Ruiz-Castillo, J. (2010). A comparison of the scientific performance of the U.S. and the European Union at the turn of the 21st century. *Scientometrics*, 85, 329–344.
- Albarrán, P., Herrero, C., Ruiz-Castillo, J., & Villar, A. (2017). The Herrero–Villar approach to citation impact. *Journal of Informetrics*, 11, 625–640.
- Archibugi, D., & Filippetti, A. (2011). Is the economic crisis impairing convergence in innovation performance across Europe? *Journal of Common Market Studies*, 49, 1153–1182.
- Bauwens, L., Mion, G., & Thisse, J.-F. (2011). The resistible decline of European science. *Recherches Économiques de Louvain*, 77, 5–31.
- Bonaccorsi, A. (2007). Explaining poor performance of European science: Institutions versus policies. *Science and Public Policy*, 34, 303–316.
- Bonaccorsi, A., Cicero, T., Haddawy, P., & Hassan, S.-U. (2017). Explaining the transatlantic gap in research excellence. *Scientometrics*, 110, 217–241.
- Bonaccorsi, A., Haddawy, P., Cicero, T., & Hassan, S.-U. (2017). The solitude of stars. An analysis of the distributed excellence model of European universities. *Journal of Informetrics*, 11, 435–454.
- Bornmann, L., & Marx, W. (2012). The Anna Karenina principle: A way of thinking about success in science. *Journal of the American Society for Information Science and Technology*, 63, 2037–2051.
- Bornmann, L., Ye, A., & Ye, F. (2018). Identifying landmark publications in the long run using field-normalized citation data. *Journal of Documentation*, 74, 278–288.
- Braun, T., Szabadi-Peresztegi, Z., & Kovács-Németh, E. (2003). No-bells for ambiguous lists of ranked Nobelists as science indicators of national merit in physics, chemistry and medicine, 1901–2001. *Scientometrics*, 56, 3–28.
- Brito, R., & Rodríguez-Navarro, A. (2018a). Research assessment by percentile-based double rank analysis. *Journal of Informetrics*, 12, 315–329.
- Brito, R., & Rodríguez-Navarro, A. (2018b). The USA is an indisputable world leader in medical and biotechnological research. *arXiv:1807.01225*.
- Celis, J. E., & Gago, J. M. (2014). Shaping science policy in Europe. *Molecular Oncology*, 8, 447–457.
- Charlton, B. G. (2007a). Measuring revolutionary biomedical science 1992–2006 using Nobel prizes, Lasker (clinical medicine)

- awards and Gairdner awards (NLG metric). *Medical Hypotheses*, 69, 1–5.
- Charlton, B. G. (2007b). Scientometric identification of elite 'revolutionary science' research institutions by analysis of trends in Nobel prizes 1947–2006. *Medical Hypotheses*, 68, 931–934.
- CREST Fourth OMC Working Group. (2009). *Mutual learning on approaches to improve the excellence of research in universities*. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2777/34314>
- Dewar, R. D., & Dutton, J. E. (1986). The adoption of radical and incremental innovations: An empirical analysis. *Management Science*, 32, 1422–1433.
- Dosi, G., Llerena, P., & Labini, M. S. (2006). The relationships between science, technologies and their industrial exploitation: An illustration through the myths and realities of the so-called 'European Paradox'. *Research Policy*, 35, 1450–1464.
- European Commission. (1995). Green Paper on Innovation. http://europa.eu/documents/comm/green_papers/pdf/com95_688_en.pdf
- European Commission. (2010). Commission staff working document. Lisbon Strategy evaluation document. *SEC(2010) 114 final*.
- European Commission. (2016). On setting up the Commission High Level Group on maximising the impact of EU Research and Innovation programmes as part of the interim evaluation of Horizon 2020. *Brussels, 21.9.2016 C(2016) 5871 final*.
- European Commission. (2017a). *Interim Evaluation of HORIZON 2020*. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2777/78199>
- European Commission. (2017b). *LAB – FAB – APP. Investing in the European future we want. Report of the independent High Level Group on maximising the impact of EU Research & Innovation Programmes*. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2777/477357>
- European Commission. (2018a). Communication from the Commission to the European Parliament, the European Council, The Council, the European Economic and Social Committee and the Committee of the Regions. A renewed European Agenda for Research and Innovation – Europe's chance to shape its future. *COM(2018) 306 final*.
- European Commission. (2018b). *EU Funding for Research and Innovation 2021–2027: European Union*. <https://doi.org/10.2777/101500>
- European Commission. (2018c). *EU Research and Innovation Success Stories*. In European Commission. (Ed.). <https://doi.org/10.2777/757994>
- European Commission. (2018d). Regulation of the European Parliament and of the Council. Establishing Horizon Europe – the Framework Programme for Research and Innovation, laying down its rules for participation and dissemination. *COM(2018) 435 final*.
- European Commission. (2018e). *Science, Research and Innovation Performance of the EU 2018. Strengthening the foundations for Europe's future*. Luxembourg: RTD-PUBLICATIONS. <https://doi.org/10.2777/14136>
- European Parliament. (2017). *EU Framework Programmes for Research and Innovation. Evolution and key data from FP1 to Horizon 2020 in view of FP9*. Brussels: European Union. <https://doi.org/10.2861/60724>
- Federal Ministry of Education and Research. (2018). Research in Germany. Lands of Ideas. <https://www.research-in-germany.org/en/research-landscape/facts-and-figures.html>. Accessed May 29, 2019.
- Filippetti, A., & Archibugi, D. (2011). Innovation in times of crisis: National Systems of Innovation, structure, and demand. *Research Policy*, 40, 179–192.
- Forés, B., & Camison, C. (2015). Does incremental and radical innovation performance depend on different types of knowledge accumulation capabilities and organizational size? *Journal of Business Research*, 69, 831–848.
- Fu, H.-Z., & Ho, Y.-S. (2013). Independent research of China in Science Citation Index Expanded during 1980–2011. *Journal of Informetrics*, 7, 210–222.
- Godin, B. (2003). The emergence of S&T indicators: Why did governments supplement statistics with indicators? *Research Policy*, 32, 679–691.
- Godin, B. (2006). On the origins of bibliometrics. *Scientometrics*, 68, 109–133.
- Gros, C. (2018). An empirical study of the per capita yield of science Nobel prizes: Is the US era coming to an end? *Royal Society Open Science*, 5, 180167.
- Heinze, T., Jappe, A., & Pithan, D. (2019). From North America hegemony to global competition for scientific leadership? Insights from the Nobel population. *PLOS ONE*, 14(4), e0213916.
- Herranz, N., & Ruiz-Castillo, J. (2013). The end of the "European Paradox". *Scientometrics*, 95, 453–464.
- Jonkers, K., & Sachwald, F. (2018). The dual impact of 'excellent' research on science and innovation: the case of Europe. *Science and Public Policy*, 45, 159–174.
- Kostoff, R. N., Briggs, M. B., Rushenberg, R. L., Bowles, C. A., Icenhour, A. S., Nikodym, K. F., ... Pecht, M. (2007). Chinese science and technology – Structure and infrastructure. *Technological Forecasting & Social Change*, 74, 1539–1573.
- Kuhn, T. (1970). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
- Leydesdorff, L., Wagner, C. S., & Bornmann, L. (2014). The European Union, China, and the United States in the top-1% and top-10% layers of most-frequently cited publications: Competitions and collaborations. *Journal of Informetrics*, 8, 606–617.
- Liu, X., Serger, S. S., Tagscherer, U., & Chang, A. Y. (2017). Beyond catch-up – can a new innovation policy help China overcome the middle income trap? *Science and Public Policy*, 44, 656–669.
- Luukkonen, T. (2014). The European Research Council and the European research funding landscape. *Science and Public Policy*, 41, 29–43.
- Martin, B. R., & Irvine, J. (1983). Assessing basic research. Some partial indicators of scientific progress in radio astronomy. *Research Policy*, 12, 61–90.
- National Science Board. (2016). *Science and Engineering Indicators 2016*. Arlington, VA: National Science Foundation.
- National Science Board. (2018). *Science and Engineering Indicators 2018*. Alexandria, VA: National Science Foundation.
- Pain, E. (2012). Research cuts will cause 'Exodus' from Spain. *Science*, 336, 139–140.
- Paradeise, C., Reale, E., Bleiklie, I., & Ferlie, E. (Eds.). (2009). *University Governance Western European Comparative Perspectives*. Berlin: Springer Science + Business Media B.V.
- Pavitt, K. (2000). Why European Union funding of academic research should be increased: A radical proposal. *Science and Public Policy*, 27, 455–460.
- Press, W. H. (2013). What's so special about science (and how much should we spend on it?). *Science*, 342, 817–822.
- Press, W. H., Flannery, B. P., Teulosky, S. A., & Vetterling, W. T. (1989). *Numerical Recipes, Fortran Version*. Cambridge, UK: Cambridge University Press.

- Ranking, CWTS Leiden. (2019). CWTS Leiden Ranking. <https://www.leidenranking.com/ranking/2019/list>. Retrieved May 27, 2019.
- Rodríguez-Navarro, A. (2009). Sound research, unimportant discoveries: Research, universities, and formal evaluation of research in Spain. *Journal of the American Society for Information Science and Technology*, 60, 1845–1858.
- Rodríguez-Navarro, A. (2011). Measuring research excellence. Number of Nobel Prize achievements versus conventional bibliometric indicators. *Journal of Documentation*, 67, 582–600.
- Rodríguez-Navarro, A., & Brito, R. (2018a). Double rank analysis for research assessment. *Journal of Informetrics*, 12, 31–41.
- Rodríguez-Navarro, A., & Brito, R. (2018b). Technological research in the EU is less efficient than the world average. EU research policy risks Europeans' future. *Journal of Informetrics*, 12, 718–731.
- Rodríguez-Navarro, A., & Brito, R. (2019). Probability and expected frequency of breakthroughs – basis and use of a robust method of research assessment. *Scientometrics*, 119, 213–235.
- Rodríguez-Navarro, A., & Brito, R. (2020). Like-for-like bibliometric substitutes for peer review: advantages and limits of indicators calculated from the e_p index. *Research Evaluation*, 29(2), 215–230. <https://doi.org/10.1093/reseval/rvaa002>
- Rodríguez-Navarro, A., & Narin, F. (2018). European paradox or delusion – Are European science and economy outdated? *Science and Public Policy*, 45, 14–23.
- Sachwald, F. (2015). *Europe's Twin Deficits: Excellence and Innovation in New Sectors*. Luxembourg: Publications Office of the European Union. <https://doi.org/10.2777/231298>
- Sandström, U., & van den Besselaar, P. (2018). Funding, evaluation, and the performance of national research systems. *Journal of Informetrics*, 12, 365–384.
- Schlagberger, E. M., Bornmann, L., & Bauer, J. (2016). At what institutions did Nobel laureates do their prize-winning work? An analysis of bibliographical information on Nobel laureates from 1994 to 2014. *Scientometrics*, 109, 723–767.
- Tijssen, R. J. W., & Winnink, J. J. (2018). Capturing 'R&D excellence': Indicators, international statistics, and innovative universities. *Scientometrics*, 114, 687–699.
- Traag, V. A., & Waltman, L. (2019). Systematic analysis of agreement between metrics and peer review in the UK REF. *Palgrave Communications*, 5, 29.
- Viiu, G.-A. (2018). The lognormal distribution explains the remarkable pattern documented by characteristic scores and scales in scientometrics. *Journal of Informetrics*, 12, 401–415.