Technological Forecasting & Social Change xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

The rate of return to investment in R&D: The case of research infrastructures

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A R T I C L E I N F O

Article history:
Received 11 October 2015
Received in revised form 10 February 2016
Accepted 22 February 2016
Available online xxxx

Jel Classifications:
O3
O4
D62

Keywords:
Return to R&D
Cost benefit analysis
Spillovers
Cost effectiveness ratio
Citation analysis
Research infrastructures

A B S T R A C T

The return to R&D investment and activities has been the object of a vast literature, both from a theoretical and empirical perspective. The aim of this overview is to present a selection of contributions to underscore the main shared findings and highlight open issues, while also providing a preliminary analysis of the returns to R&D investment in large research infrastructures (RIs) in Europe. First, a common methodological framework is distilled from the macro-literature, examining the return to R&D in aggregate terms. Then, the evaluation in the context of specific projects, mainly in large RIs, is examined, followed by the explicit consideration of externalities and spillover effects of research activities. A novel empirical analysis of European RIs is also presented, based on a novel data set, to highlight trends and suggest new avenues for the evaluation of the rate of return to investments in research infrastructures, using both a cost effectiveness ratio and a bibliometric citation count as metrics to evaluate the return to R&D investment in these facilities. Directions for future research are sketched in the concluding section.

1. Introduction

Large R&D projects, such as research infrastructures (henceforth, RIs), require substantial capital investment, mostly financed by means of public funds. The injection of significant public resources to RIs in the European Union (EU) is motivated by the recognition of their positive contribution to expanding the scientific and technological knowledge frontier, by fostering scientific discovery and acting as incubators of innovative technologies.[1] The scope of potential benefits, beyond pure knowledge, accruing to both supplier and user industries of RIs, has indeed fostered an increase in EU funds aimed at supporting RIs. From a mere €30 million allocated within Framework Programme 2 (FP2) between 1987 and 1991, €1.85 billion were committed for RIs between 2007 and 2013 in the context of FP7, and the Horizon 2020[2] Programme's budget for RIs is of around €2.5 billions between 2014 and 2020.[3] Further, an EU-wide roadmap for RIs is being implemented under the supervision of the European Strategy Forum on Research Infrastructures (ESFRI), further suggesting the attention given to this specific form of research collaboration.

Given the importance attributed to RIs for the achievement of excellence in science, innovation, and technology and the amount of funds earmarked by the EU to promote and sustain them, a better understanding of their impact on the European economy is crucial. The aim of this paper is twofold. On the one hand, it offers a critical reading of previous literature on the evaluation of the rate of return to investment in research and development (R&D) to gauge the potential benefits of RIs. On the other, the paper provides an overview of the characteristics of existing RIs in the EU and presents two possible measures (a cost effectiveness ratio and a bibliometric citation count) that can be seen as rough proxies of the rate of return to (public) investment in RIs. The empirical results presented thus suggest the dimensions along which existing and future RI projects, in different fields of science, can be examined to evaluate the potential returns to these endeavors. The goal is to frame further research on new methods to evaluate the rate of return to investment in RIs within previous literature and methodologies, while taking advantage of the stylized facts and empirical evidence concerning existing facilities in the EU.

While each project is characterized by idiosyncratic characteristics, influenced by the type of research carried out and the subject matter, that in the end determine the rate of return to capital investments, some common features and trends can be highlighted. RIs in the various fields of science may differ, for example, in terms of duration, costs, type of collaboration and partners, and countries involved, thus making comparisons in terms of a rate of return to the investment rather difficult. However, several strands of economic literature have focused on both

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[1] European Strategy Forum on Research Infrastructures (ESFRI) http://ec.europa.eu/research /infrastructures.

[2] In certain cases, RIs could also fall within the scope of cohesion policy, if they can concur to address the issues of reducing disparities among European territories and help achieve sustainable growth.

[3] Figures taken from the ESFRI website, see note 1 (retrieved online on October 2, 2014).

http://dx.doi.org/10.1016/j.techfore.2016.02.018
0040-1625/

Please cite this article as: Del Bo, C.F., The rate of return to investment in R&D: The case of research infrastructures, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.02.018

the methodological issues and the empirical analysis related to the definition and quantification of the rate of return to investment in R&D, both at an aggregate and at a project-specific level. Thus, analyzing previous literature may shed light on a reasonable numeric range for this variable and suggest a reliable methodology to analyze the impact of research investment in general, and RIs, on economic variables. Can a common framework for the evaluation and appraisal of the contribution of RIs to economic well-being and growth be identified? Can a set of stylized facts on the rate of return be distilled from the analysis of existing RIs in Europe? To this end, in what follows, a selection of previous literature on the subject is presented, mainly with the aim of identifying methodologies and best practices in the evaluation of the rate of return to capital investment in R&D, rather than presenting a systematic survey of this burgeoning literature.[4] This overview is complemented by an empirical evaluation, based on a new data set prepared for this paper, of the main characteristics of European RIs. An initial sketch of a methodology for evaluating the rate of return to investment in RIs (focusing on a cost-effectiveness measure and considering the impact of scientific publications produced within the RI) is also proposed based on data from existing facilities in the EU.

The paper is organized as follows. In Section 2, an overview of the main characteristics of RIs in the EU is presented. In Section 3, previous literature on the return to R&D is presented. First, macro-evidence, based on aggregate endogenous growth models and econometric studies is examined. Subsequently, a selection of single case studies is surveyed to analyze the methodological evolution in assessing the rates of return and overall impact of R&D activities, especially of RIs. Finally, spillover effects and externalities and implications for rate of return calculations are presented. In Section 4, an initial empirical analysis of the rate of return of existing RIs in the EU is presented. Finally, Section 5 discusses and concludes.

2. The rate of return of RIs in the EU: some stylized facts

In this section, by using a new data set on European RIs, Riportal,[5] evidence on the main characteristics of these facilities is discussed.

According to Florio and Sirtori (2014), RIs can be defined as

> "(…) high-capital intensity and long-lasting facilities and equipment, typically operating in oligopoly conditions, whose objective is to support economic development and produce social benefits through the generation of new knowledge and, often, other spillover effects." Florio and Sirtori (2014), p. 7.

The main characterizing features that emerge, apart for a long life span, are thus related, on the costs' side, to significant investment and operational costs, and on the benefits' side, to the creation of new knowledge and significant spillover effects.

Data from the Riportal website on RIs of pan-European interest provide initial information on the characteristics, by the different sectors, or fields of science, and a tentative evaluation of the rate of return associated with the major RIs in the EU. Data on single RIs, available on the website, have been collected, codified, and aggregated in a single database with information on country and sector, years since the start of the operations of the RI (age of the RI), investment and annual operational costs, employees (defined as permanent scientific/engineering staff operating the RI), annual users of the RI (distinguishing between internal and external users), and main publications produced within the activities of the RI. Quantitative and monetary data are provided in classes, so the average value for each class is considered in the following empirical analysis.

Table 1
Geographic distribution of RIs.

Country	Frequency	Percent	Country	Frequency	Percent
Austria	8	2%	Israel	3	1%
Belgium	12	4%	Italy	27	8%
Bulgaria	4	1%	Netherlands	15	4%
Cyprus	2	1%	Norway	9	3%
Czech Republic	4	1%	Other	13	4%
Denmark	5	1%	Poland	8	2%
Estonia	1	0%	Portugal	1	0%
Finland	21	6%	Romania	5	1%
France	74	22%	Spain	22	6%
Germany	53	16%	Sweden	13	4%
Greece	8	2%	Switzerland	4	1%
Hungary	6	2%	Turkey	2	1%
Iceland	1	0%	United Kingdom	17	5%
Ireland	1	0%	*Total*	*339*	*100%*

Source: author's elaboration on data from Riportal (www.riportal.eu).

After deleting RIs with missing or incomplete information, the sample is made up of 339 RIs in 27 European countries (see Table 1 for a breakdown).

Considering the spatial distribution of facilities in the EU (Table 1), France, Germany, and Italy host the highest number of RIs, accounting for, respectively, 22%, 16%, and 8% of the total.

Using the sectorial breakdown available on the Riportal website, RIs can be divided in the following fields of science (Table 2).

There is a predominance of facilities in the "hard" science fields, with 23%, 22%, and 21% of RIs, respectively, in material sciences, chemistry, and nanotechnologies; environmental, marine, and earth sciences; and physics and astronomy.

Following the definition of Florio and Sirtori (2014), and focusing on RI's salient and distinctive features, Table 3 presents information, by field, on the age of the RI, cumulated investment costs and annual operational costs (both in million €) of the RIs.

From column 1, Table 3, European RIs are shown to have an average age of 21 years, with a maximum of 28 years and a minimum of 12 in the fields of energy and information and communication technologies, mathematics, respectively. Investment costs (column 2, Table 3) are the highest in energy, followed with significantly lower figures, by material sciences, chemistry, and nanotechnologies, and physics and astronomy. Differences across fields are not so pronounced when considering the average annual operational costs (column 3, Table 3), although the previous ranking of the most costly RIs by sector is unvaried. Overall, the amounts invested to both build and operate RIs are significant and coherent with the definition of RIs presented at the beginning of the Section.

The average number of employees, i.e., permanent scientific/engineering staff operating the RI, is of 57, with wide variability across fields (column 1, Table 4).

While RIs in humanities and behavioral sciences have, on average, only 14 full-time permanent staff, more technical fields, as expected, need more specialized personnel to operate the RI. In material sciences, chemistry, and Nanotechnologies and in physics and astronomy, the average staff is of 68 and 69, respectively. The information on the labor force operating the RI is also the basis for an indicator of efficiency, computed as the ratio between the sum of investment and cumulated operational costs per employee. The lowest values are found in the fields of information and communication technologies, mathematics; life sciences; and environmental, marine, and earth sciences. The highest values are instead recorded in the fields of energy and humanities and behavioral sciences.[6] Similar conclusions can be obtained by distinguishing

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[4] For a rather comprehensive review of empirical contributions, see Hall et al. (2009), and for a general overview on the economics of science, see Audretsch et al. (2002).

[5] http://www.riportal.eu/public/index.cfm?fuseaction=ri.search. This data set has been discontinued in 2013 and has been replaced by a new data set, Meril (https://portal.meril.eu), currently covering 530 RIs. Unfortunately, the more recent data set does not provide the wealth of information on costs, employees, and users available in Riportal and has not been used for the empirical analyses.

[6] The humanities and behavioral sciences exhibits figures that are quite different from the other fields, where the cost of experiments and equipment is structurally higher. Comparisons including this specific field should therefore be interpreted with caution.

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Table 2
RIs by field of science.

Sector	Frequency	Percent
Energy	25	7%
Engineering	33	10%
Environmental, marine, and earth sciences	75	22%
Humanities and behavioral sciences	6	2%
Information and communication technologies, mathematics	4	1%
Life sciences	47	14%
Material sciences, chemistry, and nanotechnologies	78	23%
Physics and astronomy	71	21%
Total	*339*	*100%*

Source: author's elaboration on data from Riportal (www.riportal.eu)

between investment and operational costs. Excluding the field of humanities and behavioral sciences, RIs in material sciences, chemistry, and nanotechnologies exhibit the lowest cost per employee ratio, while the highest is in the Energy field, possibly indicating which sectors might be more likely to apply for additional public funds to finance the construction of the RI, given their needs in terms of total costs.

3. The rate of return to R&D in previous literature: an overview

To illustrate the importance of this topic in the academic literature and motivate the choice of an overview rather than a full-fledged survey, a search for "return to R&D" was carried out in Scopus and Web of Science.[7] In order to focus on relevant results, the search in the Scopus and Web of Science databanks was narrowed to articles, books, and reviews in Social Sciences between 1973 and 2014. Results of this selection are shown in Fig. 1.

A total of 871 and 1221 articles, respectively, in the Scopus and Web of Science databanks, have been published on the subject of the rate of return to R&D, with an increasing trend since the 1990s. These figures suggest a relevant and growing attention of the scientific community to the matter of assessing and evaluating the real impact of research activities.

Similar conclusions can be drawn by looking at citation data for these articles from 1998 to 2014 (Fig. 2). Overall, 14,984 and 19,216 articles in Scopus and Web of Science, respectively, have cited the works shown in Fig. 1 since 1998, corroborating the view that returns to R&D is an important research topic in economics.

Overall, this topic thus seems to be the object of a vast economic literature, especially in the past 20 years, with contributions in both the theoretical and empirical domain. Given the range of contributions, the strategy adopted in the present paper is to provide an overview of selected research products, with the aim of identifying the accepted knowledge on the subject and the critical issues that may benefit from further research. The underlying goal is to present a common conceptual framework and solid empirical findings which may be useful in the context of the evaluation of the rate of return of public investment in RIs, a decidedly under-researched topic in this area.

The starting point of the analysis is the literature examining the impact of R&D activities on aggregate growth, both by means of formal theoretical modeling and through sound empirical analyses and econometric estimates. The theoretical contributions are mainly framed in the context of endogenous growth models, while empirical applications include growth accounting exercises and econometric studies based on a production or cost function approach. The formalization of the problem of evaluating the rate of return to R&D, and the methods proposed to obtain numerical values that emerge from this strand of literature, are a starting point for understanding the main issues at play and applying them specifically to RIs. Further insights can be gathered by looking at the relatively less abundant literature on micro-evidence, based on case studies of specific R&D projects in different fields of science. The methodological reference is cost benefit analysis (henceforth, CBA), as outlined, for example, in Florio (2014), extended to include non-strictly financial or economic measures of output, by considering, for example, patent applications or publications. Finally, the literature on R&D externalities, or spillover effects, is examined, to stress the need for understanding the boundaries (both spatial and sectoral) of R&D activities to correctly measure their real impact and rate of return.

The insights gained from the results presented in the following Sections can be thus seen as the basis, or blueprint, for a more in depth analysis of the rate of return to this specific typology of R&D, namely, investment in RIs.

Mainly depending on the level of aggregation of the analysis, the rate of return to investment in R&D and research infrastructures[8] can take on slightly different meanings. An aggregate perspective leads to a definition of the rate of return on investment, which involves comparing the gains or profits from the investment over the amount invested. When considering a country-level or industry-level aggregation, the most commonly used methodologies involve the estimation of the elasticity of output (GDP, value added etc.) to R&D expenditures in the context of aggregate production functions or by considering the dual problem via cost functions. Looking at specific projects, the main methodological tool relies instead on the evaluation of the costs and benefits of research activities in the context of CBA. Both these approaches lead to the estimation and determination of numerical values for the rate of return to R&D. As will be clear in the following sub-sections, the range of values is quite large, and results seem to be highly dependent on the data and specific projects considered. The focus of the present paper is thus not on the actual numerical values obtained but on the methodologies adopted and the overall conclusions regarding the estimation of the rate of return to R&D.

3.1. Macro-evidence

A macro-perspective on the appraisal of the rate of return to R&D investment can help highlight the major role played by R&D in stimulating economic performance by raising productivity levels, expanding the production-possibility frontier, and engendering knowledge creation and knowledge spillovers. The relevance of R&D investment is thus key for explaining the potential benefits stemming from scientific research, while the economic return to this activity is in fact potentially difficult to gauge, the connection between the creation and diffusion of new knowledge and the potential for economic growth and development justifies the attention paid to R&D activity in the Endogenous Growth Theory.

In the latter context, in fact, in which the mechanisms ultimately explaining growth are made endogenous, knowledge capital and R&D have been formally introduced in theoretical models. Based on the neoclassical growth model (Solow, 1956; Swan, 1956), the introduction of a set of both substantial and technical improvements allows giving knowledge a prominent role as one of the most important engines of economic growth.[9]

Among many relevant contributions, three models in particular have been relevant in shaping further research on the impact of R&D. While several other theoretical contributions have been since then proposed, this selection represents an overview of the seminal contributions to the subject, which have shaped the subsequent methodological advances.

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[7] Search carried out on October 2, 2015.

[8] Another important distinction is between the private and social rate of return, with the former focusing on the costs and benefits for the individual firm investing in R&D and the latter on the benefits to society as a whole, thus including externalities and spillovers (see Salter and Martin, 2001). In general, social rate of return exceeds private rate of return due to the existence of spillover effects.

[9] The improvements include a modeling strategy, which allows for substitutability between different inputs (and, specifically, different types of capital), the asymptotic absence of diminishing returns, a representative agent framework with infinite-horizon intertemporal optimization and, in some cases, monopolistic competition as the underlying market structure (Solow, 1994).

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Table 3
Average age and costs.

Sector	Age of the RI (years)	Average cumulative investment costs (M €)	Average annual operational costs (M €)
Energy	28	139.31	6.22
Engineering	24	79.88	5.07
Environmental, marine, and earth sciences	22	49.23	4.55
Humanities and behavioral sciences	19	75.50	4.65
Information and communication technologies, mathematics	12	29.25	4.29
Life sciences	15	53.39	3.22
Material sciences, chemistry, and nanotechnologies	18	83.49	6.08
Physics and astronomy	24	84.42	5.33
Average	*21*	*74.52*	*5.07*

Source: Author's elaboration on data from Riportal (www.riportal.eu).

Romer (1990) stresses the special nature of knowledge, only part of which can be considered as totally rival and excludable. Thus, the existing stock of knowledge, in the form of fixed costs already sustained by R&D activities in the past, is available to other profit-maximising firms in the current period. In the context of profit maximization by rational agents, the existing stock of knowledge is thus considered as a production input.

Aghion and Howitt (1992) formalize the idea at the basis of Schumpeter (1942) that innovative entrepreneurs influence long run growth either by introducing new products on the market, or by improving the quality of existing products. In a recent contribution, Aghion et al. (2015) summarize what's new in Schumpeterian growth models, accounting for the results of the latest research in the field.

Young (1993), instead, models the link between formal R&D activities and the way in which new products and processes are exploited. In the model, technology evolves according to a law of motion, which represents a formalization of learning by doing. The law of motion in turn depends on the state of technology at any time, the most advanced products currently produced and labor inputs. This formulation suggests that technological change is proportional to both R&D investment and spillovers across goods, formally introducing the idea of knowledge spillovers from R&D activities.

This theoretical framework can be brought to the data at different scales of aggregation, from the firm level, to the industry level or nation-wide. Before turning to an overview of some of the most relevant empirical contributions, a general sketch of what is a common empirical methodology is proposed, in order to provide a common template for the reading of results of the macro-literature presented in what follows.

3.1.1. Theoretical Framework

Griliches (1958) and Mansfield et al. (1977) can be seen as the foundation blocks of a vast empirical literature, which has estimated the private and social rates of return to R&D in the context of formal economic modelling. To exemplify the basic concepts of the methodology adopted in this literature strand, following Hall et al. (2009), an aggregate production function[10] can be described to frame the main concepts regarding the measurement of the contribution of R&D to economic growth. Considering an economy's knowledge capital, or R&D stock, as an input to production, its rate of return can be computed. Nadiri and Mamuneas (1994) propose a method to construct the government R&D capital stock from R&D expenditures by using the perpetual inventory method with a 10% depreciation rate, which, with some variations,[11] is a methodology adopted by most of the subsequent empirical estimations of the return to R&D.[12]

The approach of evaluating the rate of return to R&D investment based on the production function methodology provides a general overview of the economic value generated by such investment. In fact, this approach actually yields marginal elasticities of output with respect to knowledge capital. Along with this classical approach, a different methodology for appraising the economic value due to R&D is based on calculating firm market values and measuring whether these increase because of new R&D investment.

The production function approach is usually implemented by means of regressing a measure of economic output on R&D within the classical production function framework (see the Appendix A). This approach requires an implicit assumption, i.e., that depreciation rates for knowledge capital are relatively low. If this assumption holds, R&D intensity (i.e., the ratio of knowledge capital on final output) can be correctly employed as a measure of R&D capital.[13]

The most widely adopted alternative methodology to evaluate the rate of return to R&D investment is by means of evaluating the impact of such investment on firm market values. In fact, from a company's perspective, the value underlying the assets of the company itself is expected to increase because new knowledge is produced by means of R&D activity. This hypothesis can be empirically tested, although the evidence is in this sense is somewhat controversial (Knott, 2012).

3.1.2. Empirical contributions

The empirical literature within Endogenous Growth Theory can help provide empirical estimates which in turn provide a first assessment of the potential benefits deriving from R&D activity of RIs, thus guiding more detailed empirical work.

Zooming in on relevant empirical contributions, Jones and Williams (1998), by focusing on the wedge between actual and optimal R&D expenditures, refer to the private return to R&D at the firm level, while the social rate of return is assessed by using industry level data. Hall et al. (2009) define the social rate of return as inclusive of spillovers (from other firms, sectors or countries), thus allowing for more general empirical models and scales of aggregation. The gap between private and social returns to R&D has been the main argument in favor of government intervention (Hall, 1996), based on the existence of externalities from R&D activity (see Section 3.2).

With the aim of presenting a numerical range for the estimated rate of return to public investments in R&D, an interesting contribution is that of Salter and Martin (2001). The authors examine the benefits of publicly funded R&D activities in basic research and survey earlier literature to provide a range of values for the social rate of return. The surveyed empirical analyses, mainly in the government sponsored

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[10] Alternatively, duality can be exploited, if the appropriate mathematical conditions are met, and the contribution of R&D to cost reductions can be examined by means of a cost function (see for example Nadiri and Mamuneas, 1994).

[11] On this issue, see also Griliches (1998).

[12] A theoretical framework to portray the production function approach proposed in the classical literature is shown in the Appendix A.

[13] It must, however, be acknowledged that regressing output on R&D intensity can potentially engender relevant downward biases in the estimates of the rate of return when R&D depreciation is not negligible. In this case, both production function and firm market value approaches require estimates of R&D depreciation, but "the two different approaches to estimating R&D returns do not agree, in that the production function approach suggests depreciation rates near zero (or even appreciation) whereas the market value approach implies depreciation rates ranging from 20 to 40 per cent, depending on the period" (Hall, 2007, p. 1).

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Table 4
Staff and costs

Sector	Average employees	Average cumulative investment costs per employee	Average cumulative operational costs per employee	Average cumulative total costs per employee
Energy	42	8.05	10.25	19.84
Engineering	66	4.39	5.52	10.03
Environmental, marine, and earth sciences	52	2.75	3.79	6.78
Humanities and behavioral sciences	14	12.58	3.65	16.23
Information and communication technologies, mathematics	42	0.91	1.65	2.56
Life sciences	40	2.73	3.30	6.03
Material sciences, chemistry, and nanotechnologies	68	3.14	3.97	7.40
Physics and astronomy	69	5.52	5.89	11.17
Average	*57*	*4.11*	*4.83*	*9.06*

Source: Author's elaboration on data from Riportal (www.riportal.eu).
Notes: employees are permanent scientific/engineering staff operating the RI.

agricultural sector, suggest a positive contribution of publicly funded R&D, corresponding to social rates of return, which evaluate the benefits to society as a whole, between 20% and 67%. [14]

Focusing more specifically on academic research, the work by Mansfield (1991, 1998) suggests an estimate of the social rate of return to academic R&D of around 28%. The basis for this point estimate is the comparison of the social benefits with or without the investment in terms of new products and processes developed and commercialized by private firms based on the results of academic R&D efforts. Benefits are hypothesized to manifest themselves with a lag of 7 years, and since firm-level data are available from 1982 to 1984, data for academic R&D refer to the period 1975–1978. The social rate of return to academic R&D is defined as the interest rate that equates the extra social benefits accruing from academic research to the level of investment in R&D.

These and similar studies have been highly influential and have been the basis for several policy initiatives aimed at fostering publicly funded academic research, as documented, for example, by the CBO Staff Memorandum (1993). It should be noted, however, that caution has been put forward against using the point estimate of 28%, suggesting instead an interpretation in terms of the order of magnitude.

Presenting more evidence in terms of a range of values for estimates of the private and social rates of return to R&D in general, the survey of earlier literature in Hall et al. (2009) suggests a wide variation across studies, depending on the level of aggregation of the data, on the time period considered and on the treatment of spillover effects. A relative consensus seems instead to emerge around the estimate range for research elasticity (γ in Eqs. (AA3) and (AA5) above), which is centered around 0.08.

Given the wide range of point estimates for both the rate of return to R&D and the related elasticities, results from two meta-analyses are reported, to provide a tentative guidance of a plausible range for these variables.

Alston et al. (2000) present the results of a meta-analysis on 289 studies of returns to agricultural R&D, with a total of 1128 observations. Empirical results suggest that, after controlling for all relevant factors, the estimated annual average rates of return to agricultural R&D, both privately and publicly funded, averaged around 65%.

A wider sectoral perspective is proposed by Wieser (2005), who provides a meta-analysis of the private rates of return to R&D and related elasticities, focusing on the impact on firm-level productivity. The results meta-analysis, based on 52 regressions from 17 studies, suggest that the mean rate of return is 28% (in line with the cited results by Mansfield, 1991, 1998), with however a range between 7% and 69%, and the mean elasticity is 0.13.

Griliches (1998) provides an explanation to the wide variability of estimates, suggesting the potential pitfalls and problems arising in the estimation of the return to R&D. A first issue is related to the distinction between a partial or total derivative of output with respect to R&D. Second, many of the variables included in the econometric specifications (R&D investment, output, past profits, productivity etc.) are collinear and simultaneous, and different solutions to establishing causality may lead to different point estimates. The distinction between basic and applied research, albeit difficult to translate in data terms, is also a potential source of variation across studies. Finally, the treatment of spillovers, the assumptions on the relevant time lag for R&D to have a real effect and the depreciation rates make comparisons across empirical analyses difficult.

The aggregate nature of the unit of observation, typically a country or region, along with the aggregate R&D expenditures considered suggest considering the evidence presented in this strand of literature more as a trend rather than as providing precise numeric values. Bronzini and Piselli (2009) show that there is a long run relationship between regional total factor productivity (TFP) levels and R&D, also providing evidence of positive spillover effects from research activities in neighboring regions. As an example of a cross-country analysis at a single sector level, Corderi and Cynthia Lin (2011) estimate the social rate of return to R&D in coal, petroleum, and nuclear manufacturing in OECD countries from 1987 to 2002. The estimation results, based on an aggregate production function and a social rate of return computed as the impact of R&D expenditures on TFP growth, suggest values ranging from 2.9% in Canada to 26.1% in Italy.

It should be noted that, notwithstanding the theoretical and empirical contributions supporting the view that R&D has a positive impact on growth, some critical views have nonetheless been put forward. In a generalized criticism to endogenous growth theories, Pack (1994) downplays the contribution of R&D to economic growth. Jones (1995), starting from the analysis of time series evidence from developed economies, while proposing a model in which the endogenous growth engine is R&D, shows that the long run growth rate ultimately depends on exogenous parameters. Comin (2004) singles out two main assumptions, which might be driving the finding of a positive and significant impact of R&D on growth and discusses their validity. In detail, more realistic definitions of the assumptions of free entry and the embodiment of R&D in innovations may lead to a lower contribution of R&D to growth and to a decrease in the size of production externalities.

3.2. Project-level evidence

Evidence provided by micro-level studies, mainly at the project level, are potentially more conducive to the identification of the order of magnitude of the rate of return to R&D infrastructure capital investment and the methodologies to be adopted to evaluate it empirically. These micro-level studies[15] may help identify patterns, for example by field of science or sector of operation, in the very heterogeneous world

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[14] Most of the contributions surveyed by the Salter and Martin (2001) perform econometric analyses in the spirit of the framework presented in Section 3.1.1.

[15] The use of the label ‘micro evidence’ may be partially misleading, since, as reported in Hall (2007), a burgeoning literature exists providing micro evidence of the impact of R&D investment on firms' market values. I would like to thank an anonymous reviewer for pointing out this issue.

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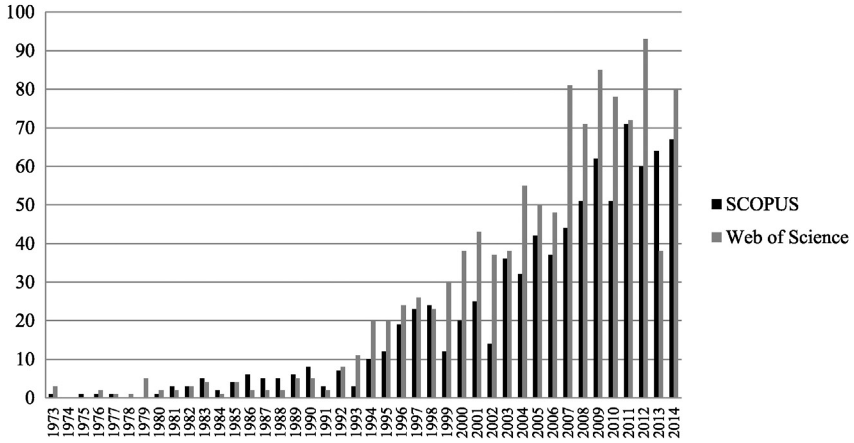

Fig. 1. Publications on the rate of return to R&D, SCOPUS and Web of Science, 1973-2014. Source: author's elaboration on SCOPUS and Web of Science data.

of RIs and suggest new avenues and methods for the evaluation of the rate of return to investment in R&D. This objective is reached by surveying the literature on R&D projects with a specific focus on RIs whenever possible, and by considering both basic and applied research, in order to disentangle the systematic component from more project-specific elements. The selected contributions presented in this Section may also suggest how to include sector or project-specific issues in a codified methodological framework to evaluate the return to R&D investment and activities in RIs.

Studies on specific RI projects can be broadly divided in two groups, according to methodological differences. The first group examines research expenditures in a CBA framework and computes internal rates of return to R&D, which can be compared to the results, in a more aggregate perspective, as outlined in Section 3.1. The second group of analyses extends the notion of return to non-financial measures and assesses the impact of R&D on knowledge creation with a varied set of metrics and methods. In what follows, rather than a comprehensive review of existing applications, a limited set of papers is surveyed for each approach, with the aim of presenting the main ideas and the most interesting avenues for going beyond simple financial analyses when evaluating the return to investment in R&D in the context of RIs.

Considering studies examining the return to research expenditures and activities in economic and financial terms, Link and Scott (2004) apply the insights of the methods for computing private and social rates of return to R&D presented in Section 3.1 to a full-fledged CBA of a case study in optical fiber networks. Examining research funded by the National Institute of Standards and Technology (NIST), the authors estimate a social rate of return to the public sector's investment by computing an economic internal rate of return (IRR) and a benefit-to-cost (BC) ratio. Data on costs and benefits are based on estimates obtained by telephone interviews to industry respondents. In detail, benefits include production cost savings related to engineering experimentation, calibration cost savings, increased production yield, negotiation cost savings, and reduced marketing costs. Costs are made up of the development costs of the infrastructure and those associated with the standard reference material purchased from NIST.

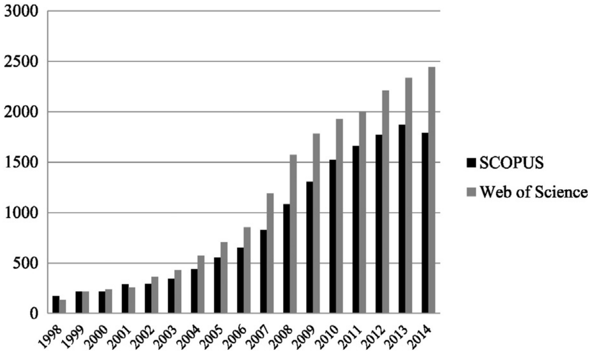

Fig. 2. Citations of publications on the rate of return to R&D, SCOPUS and Web of Science, 1998–2014. Source: author's elaboration on SCOPUS and Web of Science data.

Along a similar line of research, Montalvo (2005) provides results of a CBA exercise on the Spanish ALBA particle accelerator, reporting a value for the economic IRR of 9.4% and a benefit to cost ratio of 1.29.[16] The CBA methodology adopted follows the recommendations and computations suggested in the European Commission's Guide (European Commission, 2008), without however allowing for modifications due to the specificities of the large research infrastructure under study. Costs include investment and operational costs of the infrastructure, corrected for the negative environmental externalities when considering economic analysis, while benefits are computed by considering the opportunity cost of R&D expenditures at an aggregate, country level, thus considering benefits of the RI to society as a whole. In detail, economic benefits include those pertaining to human capital and innovation, both in terms of new knowledge and spillovers to suppliers and actors in down-stream sectors. Additional benefits, which are hard to quantify, include increased mobility and specialization of Spanish researchers involved in the project; an increase in life expectancy of the general population thanks to applied research based on ALBA's results; and finally the generation of new products or industries.

Both studies (Link and Scott, 2004 and Montalvo, 2005) can be viewed as an example of traditional CBA methods applied to publicly funded R&D projects, with some differences in the definition of the different costs and benefits considered, but with an overall similar methodological approach. A potential issue with this approach is the non-recognition of the peculiarities of large RI facilities and projects, which should require some modifications of the standard CBA procedures, as outlined in Florio and Sirtori (2014). These peculiarities relate to the significant capital investments associated to these projects, the presence of public actors, possibly from different countries, the very long terms perspective of both the infrastructure and the potential knowledge benefits associated to the infrastructure, and the typical oligopoly structure of the market.

Considering instead the second group of studies which consider non-financial measures, the recognition of the impact of R&D to the creation and accumulation of a broader notion of knowledge capital, by its own nature more difficult to measure, has prompted the use of other metrics to evaluate the success and real impact of research investment. The proponents of this approach, which will be described in greater

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[16] The magnitude of this benefit to cost ratio is in line with standard CBA studies (e.g., examples in European Commission, 2008), where values greater than 1 indicate value-creating projects.

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detail below, consider knowledge output to encompass patents, licenses, commercial and university-industry spin-offs, number of publications and citations,[17] and also include measures of quality of this output, in order to move beyond pure financial measures in the determination of the rate of return of investment in R&D. In the remainder of this section, attention will be given to the methodological advances presented by the surveyed papers, rather than focusing on the numerical values of the different measures of rate of return to R&D. This choice is motivated by the fact that the estimated figures are project-specific and might not have significant external validity per se, while the methodological innovations may be adapted to other RIs and sectors. It should be noted that the studies surveyed below all document positive rates of return to R&D in the case studies considered.

Heher (2006) provides a bridge between the traditional CBA perspective and the use of innovative measures to assess the impact of R&D by presenting an analysis of national agencies and institutions around the world. The main output and impact metric considered are licenses, patents, and commercial spin-outs from the research. The focus is on technology transfer from research carried out in public academic institutions and the potential for commercialization of results is explicitly modeled. The model's results suggest a positive rate of return to academic R&D, albeit with a significant lag of 10 to 20 years. The author explicitly models the technology transfer process and derives the rate of return to R&D as the impact on GDP of investment in research.[18] The author provides several examples and results for a range of values. This contribution, while solidly grounded in CBA theory, introduces alternative ways of measuring the real impact of academic R&D beyond financial and economic variables, linking studies on the social return to R&D to the literature on patents and licenses (e.g., Griliches, 1981; Hall et al., 2005; Arora et al., 2008).

Schultz (2011) focuses on a university-sponsored project in nanoscale science and evaluates the impact of R&D expenditure on patents and publications. While the conceptual framework adopted by the author relates to the triple helix literature (Etzkowitz and Leydesdorff, 1997), the methodology aims at evaluating, with quantifiable objectives, the impact of a university-industry state-wide (in this case New York state) collaboration.

A further step in the direction of expanding the measures available to determine the rate of return of investment in R&D (and in RIs), Hallonsten (2013) proposes a quantitative assessment of various synchrotron radiation facilities based on three metrics to gauge scientific quality. By focusing on big science accelerators, the author proposes a new set of metrics and a new methodology to assess quality and contribution to science of large research infrastructures, in this case particle accelerators. The new "facilitymetrics" is based on the percentage of scheduled operation time delivered without shutdown (a measure of the quality of the research infrastructure in terms of operation and design), oversubscription rates (a measure of the degree of competition and attractiveness to the community of the research facility), and publications (a measure more directly linked to the quality of the research output generated within the facility). This methodology represents a step forward in the direction of computing rates of return to R&D with quantifiable measures, while accounting for the specificities of large R&D infrastructures.

Finally, Hertzfeld (2002) measures economic returns from NASA's life science research by interviewing experts at private companies, which can be directly linked as spin-offs of R&D activity at NASA. This approach, based on a survey of involved actors, may be seen as a way of complementing formal CBA exercises, by providing insights on the relevant outcomes and measures which may describe impact of R&D and highlight elements influencing the social rate of return to research activities.

This zoom on selected evaluations of R&D infrastructure projects suggests the need to move beyond purely financial and economic measures and methods to assess the full impact of R&D investments, adding to the picture an assessment of benefits in terms of knowledge creation, broadly defined. An important strand of literature on the micro-evidence of the impact of R&D investment is thus also related to studies examining knowledge diffusion through patent citations (e.g., Jaffe and Trajtenberg, 1999; MacGarvie, 2005; Bacchiocchi and Montobbio, 2009; Autant-Bernard et al., 2013), which can help shed light on the regularities and determinants of the process of knowledge diffusion and decay. Focusing on the return to R&D not only on economic performance or growth, be it an aggregate or project/firm-specific scale, but extending the analysis to knowledge creation in a more general sense and thus examining the impact of research on several other dimensions should allow a more comprehensive and complete evaluation of the overall impact. The second approach, based on non-financial measures, seems more appropriate to take account of the potentially relevant non-economic returns for RIs. For this reason, in Section 4, the rate of return for European RIs is also measured by means of bibliometric indicators, along with a more traditional cost effectiveness ratio.

This potential direction for future research is explored empirically in Section 4, where two proxies for the rate of return measure are proposed and evaluated for European RIs.

3.3. Indirect impact or spillovers

The previous sections have mainly considered the impact of R&D infrastructure investment, and the related rate of return, within the unit of observation of the analysis. Macro-studies, looking at the growth potential of R&D spending nation/region/sector-wide, implicitly account for the possibility of indirect impact of disaggregated investments on the aggregate. However, a strand of literature explicitly considers the indirect impact, or spillover effect, of firm or project specific R&D investment on neighboring (defined either in geographical, technological, or sectoral terms) agents.

While most papers rely on methodologies similar to those sketched out in Section 3.1, the explicit evaluation of research externalities highlights important aspects of R&D investment and activities, which are not easily captured in a standard aggregate production function framework. Further, some unresolved issues suggest avenues for future research, such as the extension of the analysis of spillover effects from publicly funded R&D programs, as in the papers surveyed below, to the dynamics of RIs.

In an aggregate perspective, Mamuneas (1999) considers the short run effects of publicly funded R&D on the cost structure of high tech manufacturing industries in the US. His results suggest the existence of technological spillovers, which lower the variable production costs and increase private production. Bönte (2004) examines the effect of spillovers from publicly funded R&D on private R&D efforts and productivity in West-Germany manufacturing industries between 1979 and 1993. Results suggest a strong intra-industry spillover effect from public R&D to private activity and low productivity spillover effects of publicly funded R&D with respect to spillovers from private R&D in other firms. Bjørner and Mackenhauer (2013) compare private and public spillovers in the energy research sector in Denmark. The findings suggest that spillovers from private R&D on firm research activities are not higher than those from public R&D, in contrast with the previous surveyed contribution.

Zucker et al. (1998) examine the nature of knowledge spillovers from research universities in California. Their results suggest a limited

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[17] The exercise of evaluating the economic return to R&D return is structurally multifaceted. This provides the rationale for evaluating its impact also in terms of additional publications and citations. However, since some of the main results of RIs may not be circulated freely and extensively with the aim to hide information from the market, these measures could be either underestimating or distorting the actual research output of RIs. I would like to thank an anonymous reviewer for suggesting this potential issue.

[18] Assuming that the average royalty rate is of around 2–4%, and that a multiplier effect of 1.5–2 exists, if the direct economic impact of technology transfer activities is 25–50 times the revenue received by the licensing institution, an overall estimation of R&D impact can be computed.

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role of knowledge spillovers per se, while they find that the impact of academic R&D on nearby firms mainly occurs through mobility of star scientists. Monjon and Waelbroeck (2003) examine the spillover effects on firm-level performance of university-level research and R&D and find evidence of knowledge spillovers. Information flowing from universities seems to benefit more firms that imitate existing technologies or are involved in incremental innovation activities. By contrast, highly innovative firms do not seem to benefit from knowledge spillovers but rather from more formalized research collaborations with foreign universities. Zooming in more specifically on sectors and specific projects, Gnansounou and Bednyagin (2007) estimate the rate of return and spillovers from thermonuclear fusion research, examining its impact on knowledge creation and development of new products and processes and their commercialization in private firms. With a real options model, the authors show that approximately 20% of the net social economic value is represented by spillover effects.

Blind and Grupp (1999) consider the regional dimension and show how a region's technological infrastructure, as embodied in public knowledge of research institutes, positively influences private firms' innovative activities, highlighting the local dimension of spillovers. Advances in mainly publicly funded structural science in a region are found to spill over to private R&D in technologically related fields.

Overall, the literature presented above thus suggests the existence of positive spillover effects from R&D activities, both in a spatial and sectorial perspective. Open issues however remain (such as the differential behavior, if any, of private versus public research or the definition of the appropriate boundaries), paving the way for further investigations. The potential spillover effect arising specifically from RIs is another topic that has not been yet explored in the academic literature and would deserve specific attention, especially in light of the importance of externalities in defining the benefits in a CBA.

4. An empirical evaluation of the return to investment in European RIs

A new methodology, and related empirical application, to evaluate the return to investment in RIs is proposed in this section, with the aim of bridging the insights from the macro- and micro-studies presented in the previous Sections. Two measures are considered: the first can be seen as a cost-effectiveness (henceforth, CE) ratio, while the second is based on the analysis of citations of scientific publications produced within the RIs. These measures, while hindered by data availability, aim at capturing the potential of R&D in RIs to create and diffuse knowledge outside the boundaries of the facility and should be seen as a preliminary attempt to use existing data on European RIs to evaluate the return to investment. Further research based on more detailed data is needed to gauge a full-fledged rate of return to research in RIs.

While the available data does not allow the computation of a formal rate of return to the investments in RIs as outlined in the previous Sections, two alternative measures are proposed. The first, a CE ratio, compares costs and benefits, based on the implications of the Florio and Sirtori (2014) definition and on the new methods and metrics presented in the review in Section 3. This measure will be used to highlight the variability across sectors and can be seen as a first step in the evaluation of the return to investments in RIs, which goes beyond pure financial and economic output measures. The second measure considers instead the scientific and academic knowledge created by the RI[19] by considering the median citations reported in Google Scholar,[20] of the most relevant publications, as selected by the RI scientists themselves and reported to the Riportal data set, of each RI. For each RI in the database, the coordinator had to indicate the most relevant publications produced within the frame of the RI, with numbers ranging between 2 and 14. For the purpose of the present empirical analysis, only publication of articles, books and conference proceedings were considered, thus leading to a smaller sample of RIs than that used for the computation of the CE ratio (respectively, 229 versus 302). Using this bibliographic information, total citations for each publication have been retrieved from Google Scholar, while the 2013 5-year impact factor[21] for academic journals in which each entry was published was obtained from the Journal Citation Report database. Citations for each RI were then cumulated, and the median value was computed. An average impact factor for each RI was also calculated and used to construct an additional explanatory variable (see Eq. (2) below).

Focusing on the first measure that can proxy a rate of return, the underlying idea behind the CE ratio is related to the definition of the beneficiaries of RIs. While more traditional infrastructures have distinct sets of beneficiaries, such as passengers for transport infrastructures or patients in the case of healthcare infrastructures, the identification of the target group for RIs is not so clear-cut. A useful approach in defining the beneficiaries of an RI is the one suggested in Florio and Sirtori (2014), who identify many types of direct and indirect target groups. Specifically, the authors identify the main target groups[22] as businesses (both in up- and down-stream sectors with respect to the field of operation of the RI), researchers and students, the target population (e.g., patients for RIs in health application), and, to a certain extent, the general public. One group of beneficiaries, notwithstanding each RI's idiosyncratic characteristics, will most likely be always reached by the benefits and is represented by researchers and students. An RI's main output is represented by knowledge, be it in codified or implicit form, a clear benefit to the scientific community of users, which in principle includes both internal researchers to the RI and external users. Following Florio and Sirtori (2014), internal researchers which work at the research facility can be considered as the RI's staff, and as such represent an input to the production of knowledge. To this end, a conservative assumption, which will lead to an underestimation of the number of beneficiaries, assumes users to be represented only by external researchers and students.

With this background in mind, the proxy for the CE ratio is thus built as follows. Knowledge creation and diffusion, through spillover effects, are among the main benefits of an RI. We consider as an indirect proxy for knowledge creation and diffusion the number of users over the project's duration, different from the permanent staff operating the RI. Users, on the one hand, will contribute to advance knowledge by participating in the scientific and research activities of the RI and, on the other, will help the spillover process of diffusion, especially if they are external to the facility hosting the RI. On the costs' side, investment costs are added to operational costs, cumulated over the duration of the RI, to obtain a measure of the total costs of the RI over its life span. A measure of CE is thus total costs per user, with lower values indicating greater cost effectiveness of the RI, *ceteris paribus*.

Focusing instead on the second measure, the beneficiaries of knowledge produced within the RI are other scientists, and this can be gauged by considering the number of citations of the RI's publication output (for an overview of citations used in research evaluation, see for example Moed, 2005). The greater the outreach of the RI's scientific result, as summarized by a high number of citations, the greater the return to the investment in terms of scientific knowledge diffusion.

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[19] On citations as a way to assess scientific impact, see for example, Garfield (1972) for a seminal contribution and Ponomarev et al. (2014) for a recent analysis.

[20] Google Scholar is chosen as the source of information on citations in order to account for the greatest possible outreach of the academic publications produced in the RIs, not limiting them to published articles, but also including working papers, pre-prints and other publications. This choice should allow a better understanding of the spillover potential of the results of an RI.

[21] The impact factor for each publication is represented by the 5-year impact factor for 2013, provided by the Journal Citations Report database. The choice of the 5-year measure is to smooth out possible yearly swings, while the choice of the reference year, 2013, is to provide a common base for publications that have been published in different years, generally between 1999 and 2007.

[22] Not all target groups may be relevant, or to the same extent, for each RI, as facilities may be characterized by high heterogeneity only in part attributable to the field or sector to which they belong.

Please cite this article as: Del Bo, C.F., The rate of return to investment in R&D: The case of research infrastructures, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.02.018

Table 5
Cost effectiveness ratio and median citations.

Sector	Average cumulative investment costs per user (investment CE)	Average cumulative operational costs per user (operational cost CE)	Average cumulative total costs per user (CE)	Median citations (CIT)
Energy	0.055	0.083	0.140	21
Engineering	0.129	0.061	0.189	24
Environmental, marine, and earth sciences	0.051	0.036	0.090	49
Humanities and behavioral sciences	0.019	0.006	0.025	164
Information and communication technologies, mathematics	0.005	0.007	0.012	58
Life Sciences	0.041	0.019	0.061	101
Material sciences, chemistry, and nanotechnologies	0.033	0.027	0.062	70
Physics and Astronomy	0.045	0.023	0.069	108
Average	*0.052*	*0.034*	*0.087*	*75*

Source: Author's elaboration on data from Riportal (www.riportal.eu).
Notes: users are the sum of internal and external users, excluding permanent scientific/engineering staff operating the RI.

To provide some descriptive statistics of the sampled RIs, the average cumulative total costs per user, our proxy for the CE ratio (column 3, Table 5) is of 0.087 million euros, with high variability across fields. Finally, the sector average of median citations for each RI (CIT)[23] of the most relevant publications is presented in column 4, Table 5, and confirms the wide heterogeneity between fields.[24]

The highest CE ratios are in Engineering and Energy, while the lowest values are in information and communication technologies, mathematics and humanities and behavioral sciences. An interesting interpretation of these figures is related to the nature of the research output produced as a result of the activities of RIs. If in fact research and knowledge produced as a result of the RI's activities can be classified as a club good (Buchanan, 1965; Cornes and Sandler, 1996), the different values of the CE ratios across sectors can be read in terms of the relative "openness" of these clubs. Club goods are defined as being nonrival but highly excludable. In this perspective, a high CE ratio can be interpreted, on the one hand, as an indication of significant costs to entry in the club, represented, for example, by the highly specific scientific content of knowledge, which can be easily decodified by participants in the club. On the other hand, an alternative explanation is related to the number of users: if the knowledge is extremely specific, users can be few, leading to a higher CE ratio due to a denominator effect.

Focusing on citations, and excluding the fields of the Humanities and ICT (see footnote 29), the highest number of citations are documented for the fields of Physics and Astronomy and Life Sciences.

While the purpose of this exercise is not to select the fields with the lowest CE ratio or with a higher number of citations, the results can be read as suggesting that in some fields, the relatively low CE ratio and high scientific impact in terms of citations of academic publications might be indicative of a potentially relevant return to the investment, defined in a broad sense and based on the cost per users, to encompass the potential for spillover effects and knowledge creation.

To further corroborate the findings and relative ranking in Table 5, a simple correlation analysis, as in Eqs. (1) and (2), respectively, for the CE ratio and the citation measure, is performed. In Eq. (1), the rate of return as CE ratio is linked to the age of the RI project and the size of its staff, while controlling for the country where the RI is located and its sector of operations or field of science (Table 6). In Eq. (2), an additional variable is added to the model, to control for the possibility that journals with very high impact factors may induce a higher number of citations. The additional variable, *star journal*, is an indicator variable that takes on value 1 if the average impact factor of the RI's publications exceeds 10, zero otherwise (Table 7).[25] Estimation is performed by ordinary least squares with heteroskedastic-robust standard errors:

$$CE = f(\text{age}, \text{employees}, \text{sector}, \text{country}) \tag{1}$$

$$CIT = f(\text{age}, \text{employees}, \text{journal}, \text{star sector}, \text{country}) \tag{2}$$

Results, shown in Table 6, suggest that the CE ratio, as defined here in terms of average costs per external users, is negatively correlated with an RI's age and permanent staff (although the latter is statistically significant only when sector and country fixed effects are not accounted for[26]). These findings thus suggest that cost effectiveness improves over the RIs life cycle and that RIs with a longer duration might be more cost effective, and that larger RIs enjoy some form of economies of scale. Taken together, these findings suggest that average costs per users are lower, thus implying a higher rate of return, for RIs with a long duration, controlling for sector- and country-specific factors. Further, the sign and statistical significance of the estimated sector coefficients corroborate the results obtained by considering the unconditional average in Table 5.[27]

Looking instead at the determinants of citations, CIT, (Table 7), the average age of the RI appears negatively correlated with the median number of citations, while the coefficient is positive for the RI's permanent staff. The former result is easily explained by considering that results produced within younger RIs did not have many years to be read, understood, and cited. The latter result might instead suggest that the greater the number of scientists involved in the project, the higher the chance of publishing relevant results in the field's academic literature and thus the higher the number of citations. As expected, the publication in one or more star journal is highly positively correlated with the number of citations, suggesting the existence of a "reputation effect" of the publication outlet (Van Dalen and Henkens, 2001). As in Table 6, field dummy variables confirm the results of the unconditional correlation analysis, with higher citations, with respect to the base field of energy, in life sciences and physics and astronomy. It is interesting to note that this result holds even with the inclusion of the star journal variable, given the fact that the journals with the highest impact factor

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[23] The median value is considered since there is great variability in the number of citations of individual publications for some RIs, with values ranging from 10 to over 12000 in an extreme case.

[24] It should be noted that the RIs in the Humanities and ICT fields are, respectively, only two and one, so figures for these sectors should be considered with caution.

[25] The average impact factor across all fields is of 9 and the median value of 4, hence the choice of the value of 10 as a threshold.

[26] The data base analysed in this paper is structured as a cross section of RIs, many of which belong to the same Country. Hence, the use of country and sector fixed effects so as to take account of country and industrial heterogeneity. Because there is no time variation in the observed RIs, RI fixed effects proper cannot be used.

[27] The econometric results do not allow to detect a significant difference between energy and engineering.

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Table 6
Regression analysis (dependent variable: CE).

Dependent variable: CE	(1)	(2)	(3)
Average age (years)	−0.0025***	−0.0033***	−0.0035**
	0.007	*0.005*	*0.011*
Average employees	−0.0001*	−0.0002	−0.0002
	0.070	*0.125*	*0.154*
Engineering		0.0350	0.0235
		0.756	*0.833*
Environmental, marine, and earth sciences		−0.0798**	−0.1030**
		0.012	*0.020*
Humanities and behavioral sciences		−0.1438***	−0.1506***
		0.000	*0.000*
Information and communication technologies, mathematics		−0.1849***	−0.2499***
		0.000	*0.001*
Life Sciences		−0.1246***	−0.1393***
		0.000	*0.001*
Material sciences, chemistry, and nanotechnologies		−0.1122***	−0.1418***
		0.000	*0.003*
Physics and Astronomy		−0.0836***	−0.1137***
		0.002	*0.002*
Constant	0.1458***	0.2420***	0.2846***
	0.000	*0.000*	*0.000*
Country fixed effects	no	no	yes
R^2	0.0245	0.0676	0.1086
Obs.	302	302	302

Source: author's elaboration on data from Riportal (www.riportal.eu).
Notes: Dependent variable: average cumulated costs per user. *P*-values, associated to robust standard errors, in italics. Base category in column 3: Energy.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

(such as *Nature*, *Science*, *New England Journal of Medicine*, just to mention a few) are typical outlets of the two above-mentioned fields. The inclusion of country fixed effects, instead, does not seem particularly relevant.

Using citations as an indicator of RI productivity, the explanatory variable capturing the number of employees of the RI can be thought of as an input measure. The rate of return to investment in RIs is in this sense captured by the estimated parameter. The coefficient of 0.21 (column 3, Table 6) can thus be considered within the boundaries suggested in Section 3 and suggests that every additional employee is associated to an additional 0.21 citation.

Table 7
Regression analysis (dependent variable: CIT).

Dependent variable: CIT	(1)	(2)	(3)
Average age (years)	−0.7701**	−0.9586**	−0.7659*
	0.046	*0.020*	*0.052*
Average employees	0.1754*	0.2105**	0.2055**
	0.093	*0.028*	*0.013*
Star Journal	70.5376***	66.5114***	59.7509***
	0.000	*0.000*	*0.000*
Engineering		−11.7009	−7.0751
		0.344	*0.662*
Environmental, marine, and earth sciences		4.5620	−0.4723
		0.544	*0.972*
Humanities and behavioral sciences		111.2597	105.864
		0.299	*0.328*
Information and communication technologies, mathematics		17.5993**	28.3396*
		0.028	*0.086*
Life Sciences		48.4578***	53.363***
		0.000	*0.001*
Material sciences, chemistry, and nanotechnologies		2.7958	9.4632
		0.797	*0.531*
Physics and Astronomy		60.9876***	42.4768***
		0.000	*0.006*
Constant	56.9458***	36.4699***	20.8299
	0.000	*0.000*	*0.453*
Country fixed effects	no	no	yes
R^2	0.2143	0.3169	0.4913
Obs.	229	229	229

Source: author's elaboration on data from Riportal (www.riportal.eu).
Notes: Dependent variable: median citations for top publications in Google Scholar. *P*-values, associated to robust standard errors, in italics. Base category in column 3: Energy.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

More data on the actual output, in terms of knowledge creation and innovative results produced by RIs, would be needed to provide a clearer picture of the underlying mechanisms. However, this empirical exercise can be seen as an initial attempt to move beyond the aggregate, macro, approach to determining the rate of return of RIs, blending insights from the project, micro-level studies, in a unified framework.

5. Open issues and concluding remarks

The aim of the overview of earlier contributions examining the rate of return to R&D has been to identify common patterns in terms of results and methodologies adopted when evaluating the contribution of R&D investment to productivity and growth, and to highlight open issues, thus suggesting promising avenues for future research. The selection has also been influenced by the need to identify contributions useful to the definition of a framework for evaluating the impact of R&D in large RI projects. A first, tentative empirical exploration of the characteristics of RIs in the EU and the differences across sectors of their CE ratio and median citations of research output has also been presented.

In a nutshell, the aggregate, macro-evidence, suggests a positive contribution of investment in R&D to economic growth and productivity, both from a theoretical standpoint and with empirical analyses and performed using different econometric techniques. The disaggregated, micro-evidence, links R&D investments to a broader set of variables, including performance, innovation, and research output. The consideration of the spillover effects, or externalities, of R&D activities suggests the importance of its partial non-rival and non-excludable characteristics which should be accounted for when evaluating its impact on economic activity and knowledge creation.

The critical reading of previous results suggests however some open issues, which could benefit from more in depth studies. A preliminary issue is related to notation and terminology, as the use of the term "rate of return" may sometimes be confusing as different studies, especially differing in the disaggregation (macro or micro) scale considered, have used the same term but have proposed different estimation and computational frameworks. This issue becomes even more poignant once RIs are considered, given the very diverse nature of activities, and thus, of costs and benefits, depending on the field of science. As the preliminary empirical examination of the CE ratio and median citations of European RIs has shown, results vary across significantly sectors, both in terms of the unconditional and conditional CE and median citation value and of the underlying dynamics of costs and benefits associated to the RIs. Further micro-level research on existing European RIs would be thus worth pursuing, with the aim of identifying the critical factors of success of RIs. The preliminary results presented here in terms of different CE ratios and number of citations across fields of science should not be read as suggesting in which sector investment in RIs should be concentrated but should be suggestive of the different characteristics of RIS in the various fields. A more elaborate definition of the rate of return, which could account for the structural differences across fields of science, while providing a common framework, should also be developed.

A related issue is the prevalence of macro-level analyses on the returns to aggregate R&D investment, with a set of common and accepted methodologies and findings, with respect to more micro-level studies. The existing micro-case studies are a first step in defining a methodology for the assessment and appraisal of investments in RI, although more research is needed to reach a consensus regarding both methodologies and data requirements, as more or less has happened in the more macro-oriented literature. A full-fledged CBA model for RI

Please cite this article as: Del Bo, C.F., The rate of return to investment in R&D: The case of research infrastructures, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.02.018

is not yet available, although initial attempts are presented by Florio and Sirtori (2014). Further research is thus needed to have a clearer picture of the social costs and benefits associated with RIs in different fields of science, and more in depth micro-level case studies of existing RIs could provide a basis for further generalizations, while highlighting the specific characteristics if RIs that set them apart from other R&D projects.

Another relevant aspect, which has not been fully accounted for by existing literature, especially in the context of the development of a CBA model for RIs, is related to the time lag over which R&D investment and activities exerts its impact. Most studies are constrained by the data both in terms of availability of a time series dimension and differ in terms of level of aggregation and scope of the analysis, thus explaining the lack of an agreed upon time frame. This issue is however important, also from a policy perspective, and could be especially useful when considering large RI projects. A related issue is that of the role of inter-industry versus intra-industry spillovers of R&D investment (definition of a project's thematic boundaries) and spillovers from different regions or countries (definition of a project's geographic boundaries). These spillovers should be better evaluated and quantified and an open issue is related to the definition of the distance (physical, technological and sectorial) over which spillover effects may exert an impact.

A critical discussion of previous contributions has thus provided a better understanding of the structural determinants of the rate of return to R&D investment, and a methodological roadmap for defining appropriate models for its determination in the context of large research infrastructure projects. The analysis of existing RIs in the EU, based on a comprehensive data set provided by ESFRI, has allowed to analyze the cross-country and cross-sector characteristics of these facilities and provide some insight on age of the RI since its inception, staff, costs, and users. The proposed formulation of a CE ratio in RIs, based on the computation of average costs per users of the RI, and the bibliometric measure, suggest two considerations. On the one hand, the peculiarity of RIs require the need to move beyond simple aggregate, macro-measures of the rate of return, and use the insights from the micro-level studies to develop more complex measures of the potential return to investments in RIs. On the other hand, the simple descriptive statistics and correlation analysis suggest the need to properly account for field, or sectorial differences, which influence the efficiency and relation between costs and benefits greatly.

Appendix A. Technical Appendix

Considering a Cobb Douglas specification for simplicity,[28] aggregate output or production (Y) is a function of a labor input (L), tangible capital (C), and own knowledge capital (K), with A representing technical knowledge and u a disturbance term:

$$Y = AL^{\alpha} C^{\beta} K^{\gamma} e^{u} \tag{A1}$$

Taking logs of Eq. (A1) and assuming that μ is made up of individual (i), time (t) and individual-time (it) fixed effects, leads to

$$y_{it} = \eta_i + \lambda_t + \alpha l_{it} + \beta l_{it} + \gamma k_{it} + u_{it}, \tag{A2}$$

with subscript i representing countries, firms or sectors and t time, and η_i represent individual fixed effects.

In growth terms:

$$\Delta y_{it} = \Delta\lambda_{it} + \alpha\Delta l_{it} + \beta\Delta c_{it} + \gamma\Delta K_{it} + \Delta u_{it}, \tag{A3}$$

where $\Delta K_{it} \equiv \frac{k_{it} - k_{it-1}}{k_{it-1}}$

Eq. (AA3) represents the first differenced version of Eq. (A2). The use of time differentials allows to cancel out individual fixed effects.

Knowledge capital is derived from R&D expenditure by means of the following perpetual inventory method:

$$K_{it} = (1-\delta)K_{it.1} + R_{it} \tag{A4}$$

where δ is the depreciation rate and R is real R&D investment.

After some manipulation, plugging Eq. (A4) into Eq. (A3) leads to

$$\Delta Y_{it} = \lambda_t + \alpha\Delta l_{it} + \beta\Delta c_{it} + \gamma\frac{R_{it} - \delta k_{it-1}}{k_{it}} + \Delta u_{it} \tag{A5}$$

Notice that γ is the marginal elasticity of output with respect to k, i.e., $\gamma \equiv \rho\frac{K}{Y}$, where ρ is the marginal productivity of R&D capital, i.e., $\rho \equiv \frac{\partial Y}{\partial K}$.

Eq. (A5) can thus be rewritten as

$$\Delta Y_{it} = \lambda_t + \alpha\Delta l_{it} + \beta\Delta c_{it} + \rho\frac{R_{it} - \delta k_{it-1}}{y_{it}} + \Delta u_{it}, \tag{A6}$$

where ρ can be seen as the marginal gross (of depreciation) internal rate of return to R&D. If the depreciation rate δ is approximately zero,[29] a simple measure of R&D capital can thus be R&D intensity, computed as R&D over output.

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[28] Alternative specifications include a more general translog specification, used for example in the infrastructure capital literature (on this issue see Canning and Bennathan, 2000).

[29] On the issues related to depreciation, see Hall (2007).

Please cite this article as: Del Bo, C.F., The rate of return to investment in R&D: The case of research infrastructures, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.02.018

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Please cite this article as: Del Bo, C.F., The rate of return to investment in R&D: The case of research infrastructures, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.02.018