The Rate of Return to Research and Development in Energy*

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Abstract

This paper estimates the rate of return to research and development in the energy industry accounting for intra-industry spillover effects within each country. In particular, we estimate the effect of research and development on total factor productivity growth in the energy-related products manufacturing industry and in the electricity, natural gas, and water supply industries for a number of OECD countries, using a panel of data from the EU KLEMS and OECD ANBERD databases. Unlike previous work estimating rates of return to R&D, which use data based on an obsolete methodology for measuring productivity that leads to an upward bias in the estimated rates of return, we use data based on the correct methodology for measuring productivity. In addition, we account for intermediate inputs, including energy, materials, and services, in our production function. Our results suggest that research and development has a positive and significant rate of return in France, Finland, and the Netherlands.

Keywords: rate of return to R&D, energy, R&D

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1. Introduction

Owing to mounting geopolitical, environmental, and economic concerns, investment in research and development (R&D) in the energy sector has become increasingly crucial for sustainability, security, and environmental protection. A 1997 report from the U.S. President's Committee of Advisors on Science and Technology and a 2004 report from the bipartisan National Commission on Energy Policy each recommended that federal R&D spending be doubled. Several groups have called for even larger commitments, on the scale of the Manhattan Project of the 1940s (Kammen & Nemet, 2005). In OECD countries, fossil fuel R&D drives economic growth more than fossil fuel consumption (Wong, Chang & Chia, 2013).

Since the mid-1990s, however, both public and private sector investment in R&D in the United States has stagnated for renewable energy and energy efficiency, and has declined for fossil fuel and nuclear technology (Corderi & Lin, 2011; Kammen & Nemet, 2005; Lynd, 2004). These declines are neither new nor unique to the United States: between 1980 and 1995, international R&D fell 39 percent for energy and 56 percent for renewable energy (Margolis & Kammen, 1999b).

According to economic theory, there are several reasons why the private rate of R&D may diverge from the socially optimal rate of R&D. First, firms may under-invest in R&D because there are positive spillovers involved: when a firm makes a discovery, other firms can free ride on the invention and may even imitate the invention without having paid for the R&D efforts. Even with patent protection, these spillovers reduce the payoff to investing in R&D. A second reason why the private rate of R&D is lower than the optimal rate is the appropriability effect: in the absence of perfect price discrimination, the private surplus from innovation is lower than the social surplus (Tirole, 2001). A countervailing effect that leads firms to over-invest in R&D is the business-stealing effect: a firm that introduces a new product does not internalize the loss of profit suffered by its rivals on the product market (Tirole, 2001). Thus, market imperfections may lead to either overinvestment or underinvestment in R&D relative to its socially optimal level (Romer, 1990; Aghion & Howitt, 1992; Grossman & Helpman, 1991).

Measuring the size of distortions to R&D investment relative to its socially optimal level is not an easy task, however. Jones and Williams (1998) measure the overall effect of distortions in R&D using an endogenous growth model, and conclude that optimal R&D investment in the U.S. is at least twice as large as the actual level of R&D investment in the U.S. Bloom, Schankerman and Van Reenen (2013) develop and estimate a model that incorporates both positive and negative spillovers to R&D using panel data on U.S. firms, and find that positive technology spillovers quantitatively dominate negative business stealing effects, so that the gross social returns to R&D are at least twice as high as the private returns. Margolis and Kammen (1999a, 2001) examine the energy sector in the U.S. and conclude that there has been a sustained pattern of underinvestment.

A crucial parameter needed in order to determine the optimal level of R&D investment is the rate of return to R&D investment. This rate of return measures how much productivity increases as a result of investment in R&D. In principle, we would want to estimate a rate of return to R&D investment that accounts for R&D spillovers. Findings in the empirical productivity literature (Griliches, 1992) emphasize that rates of return to R&D investment that account for R&D spillovers are significantly higher than those that do not.

There are several different types of spillover accounted for by previous studies that empirically estimate the rate of return to R&D. One type of spillover accounted for by previous studies are intra-industry spillovers. These studies regress total factor productivity (TFP) growth on R&D intensity, where R&D intensity is measured as the ratio of privately financed R&D spending to sales revenue (see e.g., Sveilkauskas, 1981; Griliches & Lichtenberg, 1984b; Griliches, 1994).

A second type of spillover accounted for by previous studies empirically estimating the rate of return to R&D are inter-industry spillovers. These authors capture the effect of R&D in one industry on measured productivity in other industries. Many use a technology flow matrix constructed from patent data or input-output flows between industries to impute the inter-industry spillovers (see e.g., Terleckyj, 1980; Scherer, 1982; Griliches & Lichtenberg, 1984a; Adams & Jaffe, 1996). Jaffe (1986) incorporates R&D from other industries into the R&D stock used to estimate productivity gains.

A third type of spillover accounted for by previous studies empirically estimating the rate of return to R&D are international spillovers. These studies capture the effect that foreign R&D has on domestic productivity through trade (see e.g., Coe & Helpman, 1995; and Nadiri & Kim, 1996; Taegi & Park, 2003). Several authors have followed the same approach but have also corrected for human capital effects and depreciation of the R&D stock (see for example Engelbrecht , 1997; Griffith, Redding and Van Reenen, 2000; Keller, 2002, 2004).

It is possible that the rate of return to R&D, particularly energy R&D, may be diminishing. Popp (2006) examines energy patent citations over time and finds evidence for diminishing returns to research inputs, both across time and within a given year. However, Popp et al. (2013) find that while diminishing returns will be most problematic during rapid increases of research investment, such as that experienced by solar energy in the 1970s, positive spillovers may occur at moderate levels of research activity. They thus conclude that diminishing returns to additional research inputs need not automatically be assumed.

This paper provides estimates of the rate of return to R&D in energy-related industries for a number of Organisation for Economic Co-Operation and Development (OECD) countries. We use industry-level productivity and R&D intensity measures to capture inter-firm technology spillovers in the manufacturing of coal, petroleum products and nuclear fuel as well as in the electricity, gas, and water supply industries.[4] By considering only intra-industry spillover effects within a country, our estimates capture a lower bound for the social rate of return to R&D investment.

Our paper builds upon the work of Corderi and Lin (2011), who estimate the rate of return to R&D in coal, petroleum, and nuclear manufacturing, and the work of Inglesi-Lotz (forthcoming), who estimates the rate of return to R&D on various energy technologies, in several ways. First, nearly all previous work estimating rates of return to R&D, including Corderi and Lin (2011) and Inglesi-Lotz (forthcoming), use data that employs an obsolete methodology for measuring productivity (Jorgenson, 2009). As a result, the estimated rates of return are estimated are biased upward, possibly severely. To remedy this problem, we use the EU KLEMS data base, which is based on the correct methodology for measuring productivity.

The EU KLEMS data base that we use differs from the data used by nearly all previous work estimating rates of return to R&D, including Corderi and Lin (2011) and Inglesi-Lotz (forthcoming), in that it replaces net national product (NNP) with gross national product (GNP) as a measure of output and uses constant quality indexes for both capital and labor inputs. The constant quality index of labor input distinguishes among different types of labor inputs, thus extending the concept of substitution to include not only the substitution between capital and labor inputs considered in previous data sets employing the obsolete methodology for measuring

[4] The data unfortunately do not enable us to separate out the electricity and gas industries from the water supply industry, as these industries are aggregated together.

productivity, but also substitution between different types of labor inputs. Allowing for substitution between different types of labor inputs has significant consequences for the allocation of economic growth between substitution and technical change (Jorgenson, 2009). Similarly, the constant quality index of capital input in the data we use distinguishes among different types of capital inputs (Jorgenson, 2009). Jorgenson and Griliches (1967) show that changes in the quality of capital and labor inputs and quality of investment goods explain most of the Solow residual.

The EU KLEMS data base that we use also differs from the data used by nearly all previous work estimating rates of return to R&D in that the aggregate production function is replaced by a production possibility frontier, thus allowing for joint production of consumption and investment goods from capital and labor inputs (Jorgenson, 2009).

The new, correct methodology for measuring productivity used in constructing the EU KLEMS data base has made the previous methodology, which was based on the conventions of Kuznets (1971) and Solow (1970) and which has been used by nearly all previous work estimating rates of return to R&D, obsolete. The new framework for productivity measurement is outlined in a manual published by the OECD (Schreyer and Pilat, 2001) which establishes international standards for measuring productivity. The new, correct methodology for measuring productivity is also now used by the U.S. Bureau of Labor Statistics (Jorgenson, 2009). The EU KLEMS data set we use provides industry-level productivity measurements based on this new framework for growth accounting (Jorgenson, 2009).

In addition to using the correct methodology for measuring productivity, the second way in which we build upon Corderi and Lin (2011) and Inglesi-Lotz (forthcoming) is that we account for intermediate inputs, including energy, materials, and services, in our production function.

Third, unlike Corderi and Lin (2011) and Inglesi-Lotz (forthcoming), the data used in this paper includes a breakdown of hours worked by type of worker; a breakdown of investment into various asset types; and a calculation of capital stocks and services using a harmonized methodology.

Fourth, we expand the set of countries examined, from the 13 countries examined by Corderi and Lin (2011) and the 7 countries examined by Inglesi-Lotz (forthcoming), to 16 countries.

The fifth way in which we build upon Corderi and Lin (2011) is that we analyze the energy-related products manufacturing industry and the electricity, gas, and water supply industry instead of coal, petroleum, and nuclear manufacturing. Sixth, we update the time period examined from the 1987-2002 period examined by Corderi and Lin (2011) to the longer period of 1987-2006.

The paper is organized as follows. Section 2 outlines our theoretical framework for estimating the rate of return. Section 3 presents a description of the data used in our study. Section 4 outlines our empirical estimation strategy. Section 5 contains an overview of the estimation results. Finally, section 6 concludes and discusses possible ideas for expanding this research in the future.

2. Theoretical Framework

Our theoretical framework builds on that of Jones and Williams (1998) and Corderi and Lin (2011) by accounting for intermediate inputs, including energy, materials, and services. In particular, we adopt a Cobb-Douglas production function of the form:

$$Y_t = e^{\mu t} Z_t^{\gamma} K_t^{\alpha} L_t^{\beta} E_t^{\delta_1} M_t^{\delta_2} S_t^{\delta_3}, \qquad (1)$$

where Y denotes output produced; Z denotes the R&D stock; K denotes capital; L denotes labor; E denotes energy; M denotes materials; S denotes service; and μ, γ, α, β, δ_1, δ_2, and δ_3 are constants.

The equation of motion for R&D stock Z is given by:

$$\dot{Z}_t = R_t, \tag{2}$$

where R denotes expenditures on R&D. We assume that the R&D stock does not depreciate.

Total factor productivity (TFP) is given by:

$$TFP_t = e^{\mu t} Z_t^{\gamma}. \tag{3}$$

Thus, TFP increases over time through the factor $e^{\mu t}$ as well as through investments in the R&D stock Z. After substituting equation (3) for TFP into equation (1) for the production function and rearranging, we can derive the following relationship between TFP and output Y:

$$TFP_t = \frac{Y_t}{K_t^{\alpha} L_t^{\beta} E_t^{\delta_1} M_t^{\delta_2} S_t^{\delta_3}}. \tag{4}$$

The rate of return $\tilde{r}$ to R&D is given by the derivative of output Y with respect to R&D stock Z:

$$\tilde{r} = \frac{dY}{dZ}. \tag{5}$$

Combining equations (1), (2), and (3), and following some manipulation, we get the following equation for the growth rate in TFP:

$$\frac{\dot{TFP}_t}{TFP_t} = \mu + \tilde{r}\frac{R_t}{Y_t}, \tag{6}$$

where $\tilde{r}$ is the rate of return to R&D. See Appendix A for details of the derivation.

To empirically estimate equation (6), we regress total factor productivity growth $\frac{\dot{TFP_t}}{TFP_t}$ on the R&D share of output $\frac{R_t}{Y_t}$. The estimated coefficient $\tilde{r}$ in equation (6) corresponds to our desired measure of the rate of return to R&D. As Jones and Williams (1998) point out, $\tilde{r}$ can represent the private rate of return if we use firm-level data and accounts for intra-industry spillovers if we use industry-level data.

By using industry-level data, we estimate the rate of return to R&D in energy-related industries for a number of OECD countries. We use industry-level productivity and R&D intensity measures to capture inter-firm technology spillovers in the manufacturing of coal, petroleum products, and nuclear fuel as well as in the electricity, gas, and water supply industries. By considering only intra-industry spillover effects within a country, our estimates capture a lower bound for the social rate of return to R&D investment.

Several remarks should be made before proceeding to the actual analysis of the data. First, by considering only intra-industry spillover effects within a country, we do not allow for the possibility of R&D spillovers between industries. Second, we are not capturing intertemporal knowledge spillovers or congestion effects. Third, we are working under the assumption of a "closed economy", which means that we do not account for technological diffusion through trade. Fourth, we do not account for potential benefits of R&D in technology to reduce the pollution intensity of energy output. These assumptions will give us, in principle, a lower bound estimate of the social rate of return.

3. Data

3.1 Energy R&D and Output

We use data for two energy related industries. The first industry is the manufacturing of coke, petroleum products, and nuclear fuel industry[5] for 16 OECD countries over the years 1987-2006. The countries are Australia, Belgium, Canada, Czech Republic, Finland, France, Germany, Hungary, Italy, Japan, Korea, Netherlands, Spain, Sweden, United Kingdom, and United States.

The second industry we study is the electricity, natural gas, and water supply industry[6] for 17 OECD countries available over the years 1987-2006. The countries are the 16 countries above plus Denmark.

Our data on input, output, and prices comes from the EU KLEMS[7] database (http://www.euklems.net). We use industry value added as our measure of output.

The source for R&D expenditure[8] data is the Annual National Business Expenditures on Research and Development (ANBERD)[9] database, OECD (2010). Our sample of countries accounts for at least 85 percent of OECD value added in these specific industries. Moreover, R&D expenditures by these countries constitute at least 90 percent of the OECD's innovative activity and almost all business R&D in these two energy-related industries between 1987 and 2006.

Table 1 shows a summary of output and R&D data available for the energy-related products manufacturing industry. Industry value added and R&D data (R&D expenditures and R&D intensity) are averaged over the periods 1980-2006 and 1987-2006, respectively, for each of the

[5] This industry corresponds to ISIC (Review 3) number 23.
[6] This industry corresponds to ISIC (Review 3) number 40.
[7] Data is available for the period 1980-2006.
[8] We use data on total business enterprises R&D irrespective of source of funding.
[9] We alternatively reconstruct R&D expenditures from the R&D capital stock data available in the EU KLEMS database; recovered R&D expenditure data is available for the period 1980-2002. The correlation between R&D expenditures from the ANBERD database and the recovered R&D expenditures from EU KLEMS is 0.99, with a p-value of 0.00.

countries in the study sample. We can see that both industry value added and R&D expenditures vary substantially across countries.[10] The G-7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom and the United States) conduct on average 90 percent of the energy-related products manufacturing R&D in the sample and produce on average 80 percent of the energy-related products manufacturing industry value added. R&D expenditures are the highest in the United States, which conducts more than 50 percent of the R&D in the entire sample, followed by Japan and United Kingdom at 11 and 9 percent, respectively. Industry value added is highest in Japan and the United States, which represent 29 and 22 percent of the industry value added in the entire sample, respectively, followed by Germany and France at 9 and 7 percent, respectively.

[10] We are using Purchasing Power Parity exchange rates (PPPs) to compare across countries as in Bernard and Jones (1996). It is important to note that PPPs neither are industry specific nor do they reflect relative producer prices. Conversions of industry-level indicators to a common currency based on PPPs should therefore be interpreted with caution.

TABLE 1: R&D and Output in the Energy-Related Products Manufacturing Industry

	R&D Expenditures			Industry Value Added		
Country	Mean *	Relative Size (%)	R&D Intensity **	Mean ***	Relative Size (%)	Share of GDP ****
Australia	23.02	0.69%	1.54%	1204.22	1.08%	0.23%
Belgium	45.40	1.37%	4.33%	2622.60	2.34%	0.56%
Canada	97.88	2.95%	6.46%	1827.72	1.63%	0.28%
Czech Republic	7.37	0.22%	0.51%	3002.34	2.68%	0.39%
Finland	18.45	0.56%	5.46%	422.28	0.38%	0.50%
France	245.83	7.41%	5.75%	8676.29	7.75%	0.61%
Germany	55.25	1.67%	2.37%	10446.16	9.33%	0.29%
Hungary	15.79	0.48%	0.70%	3962.03	3.54%	1.69%
Italy	35.73	1.08%	0.77%	7829.58	6.99%	0.43%
Japan	377.01	11.36%	1.22%	33277.46	29.72%	1.12%
Korea	102.14	3.08%	1.98%	3648.62	3.26%	1.19%
Netherlands	48.61	1.47%	4.69%	1694.95	1.51%	0.41%
Spain	46.86	1.41%	1.36%	4136.74	3.69%	0.58%
Sweden	11.70	0.35%	3.81%	683.17	0.61%	0.18%
United Kingdom	306.45	9.24%	7.91%	3854.50	3.44%	0.49%
United States	1879.80	56.67%	6.24%	24685.82	22.05%	0.42%
G-7 *****	2997.94	90.37%		90597.52	80.91%	
Total	3317.28	100.00%		111974.47	100.00%	

* Average R&D expenditures over the period 1987-2006, measured in million 2000 $ U.S. constant PPP.
** Average R&D intensity over the period 1987-2006, measured as the ratio of R&D expenditures to industry value added.
*** Average industry value added over the period 1980-2006, measured in million 2000 $ U.S. constant PPP.
**** Average share of industry value added relative to country GDP over the period 1980-2006.
***** The G-7 countries are: Canada, France, Germany, Italy, Japan, United Kingdom, and United States.

Table 2 shows a summary of output and R&D data available for the electricity, natural gas and water supply industries. Industry value added and R&D data (R&D expenditures and R&D intensity) are averaged over the periods 1980-2006 and 1987-2006, respectively, for each of the countries in the study sample. We can see that both industry value added and R&D expenditures vary substantially across countries. The G-7 countries conduct on average 81 percent of electricity, natural gas and water supply R&D in the sample and produce on average 84 percent of the electricity, natural gas and water supply industry value added. R&D expenditures are highest in Japan, France, and the United States, which represent respectively 26, 16, and 13 percent of total R&D expenditures in the entire sample. It should be noted that this industry is not as intensive in R&D as the energy-related products manufacturing industry. Industry value added is highest in the United States and Japan, which represent 35 and 20 percent of the industry value added in the entire sample, respectively, followed by Germany and Italy at 7 and 6 percent, respectively.

TABLE 2: Descriptive Statistics for the Electricity, Natural Gas and Water Supply Industries

	R&D Expenditures			Industry Value Added		
Country	Mean *	Relative Size (%)	R&D Intensity **	Mean ***	Relative Size (%)	Share of GDP ****
Australia	40.87	1.93%	0.34%	11243.11	2.56%	3.12%
Belgium	13.32	0.63%	0.24%	5148.34	1.17%	2.97%
Canada	182.09	8.58%	0.89%	20331.75	4.62%	3.02%
Czech Republic	1.63	0.08%	0.02%	5691.87	1.29%	4.37%
Denmark	3.60	0.17%	0.16%	2232.46	0.51%	2.07%
Finland	28.45	1.34%	1.50%	1828.96	0.42%	2.52%
France	346.76	16.34%	1.77%	17369.09	3.95%	1.91%
Germany	79.75	3.76%	0.28%	34494.52	7.84%	2.39%
Hungary	6.83	0.32%	0.16%	5392.06	1.23%	3.23%
Italy	93.71	4.42%	0.43%	28416.51	6.46%	1.95%
Japan	556.63	26.23%	0.55%	92305.31	20.98%	3.44%
Korea	136.57	6.43%	1.45%	12247.16	2.78%	2.46%
Netherlands	16.61	0.78%	0.27%	5284.06	1.20%	1.85%
Spain	90.65	4.27%	0.50%	14519.61	3.30%	2.44%
Sweden	57.08	2.69%	1.10%	5132.27	1.17%	2.97%
United Kingdom	191.49	9.02%	0.90%	21770.00	4.95%	2.39%
United States	276.36	13.02%	0.15%	156485.76	35.57%	2.30%
G-7 *****	1726.79	81.36%		371172.93	84.38%	
Total	2122.40	100.00%		439892.84	100.00%	

* Average R&D expenditures over the period 1987-2006, measured in million 2000 $ U.S. constant PPP.
** Average R&D intensity over the period 1987-2006, measured as the ratio of R&D expenditures to value added.
*** Average value added over the period 1980-2006, measured in million 2000 $ U.S. constant PPP.
**** Average share of value added relative to country GDP over the period 1980-2006.
***** The G-7 countries are: Canada, France, Germany, Italy, Japan, United Kingdom, and United States.

3.2 Total Factor Productivity

We use Tornqvist indexes to calculate total factor productivity growth rates, which is a superlative-index-number approach suggested by Caves, Christensen, and Diewert (1982). Writing equation (4) for TFP in terms of growth rates, we obtain:

$$\frac{\dot{TFP}_{it}}{TFP_{it}} = \frac{\dot{Y}_{it}}{Y_{it}} - \alpha_{it}\frac{\dot{K}_{it}}{K_{it}} - \beta_{it}\frac{\dot{L}_{it}}{L_{it}} - \delta_{1it}\frac{\dot{E}_{it}}{E_{it}} - \delta_{2it}\frac{\dot{M}_{it}}{M_{it}} - \delta_{3it}\frac{\dot{S}_{it}}{S_{it}}, \tag{7}$$

where α_{it}, β_{it}, δ_{1it}, δ_{2it}, and δ_{3it} are respectively the labor, capital, energy, materials, and service input shares of the value added in the energy-related industry of country *i* at time *t*.

All data used for the construction of the total factor productivity growth rate comes from the EU KLEMS database (http://www.euklems.net), unless otherwise noted.[11] Unlike data used in previous studies estimating rates of return to R&D, which employ an obsolete methodology for measuring productivity (Jorgenson, 2009), the EU KLEMS data base is based on the correct methodology for measuring productivity. A more detailed description of the EU KLEMS database is available in O'Mahony and Timmer (2009).

Variables in equation (7) are obtained as follows. Nominal and price series for output and total intermediate inputs at the industry level are taken directly from the National Accounts. As these series are often short (as revisions are not always taken back in time), different vintages of the national accounts were bridged according to a common link-methodology.

Output Y_{it} is measured as industry gross value added. Labour service input L_{it} is based on series of hours worked and wages of various types of labour. Capital input K_{it} by industry is generally not available from the National Accounts. The basic investment series by industry and

[11] Some of countries did not have a complete time series of the variables. Czech Republic, Hungary and Sweden did not have data available before 1995.

asset have been derived from capital flow matrices and benchmarked to the aggregate investment series from the National Accounts. For each individual asset, stocks have been estimated on the basis of investment series using the perpetual inventory method (PIM) with geometric depreciation profiles. Depreciation rates differ by asset and industry but have been assumed identical across countries. Data on intermediate inputs are broken down into energy E_{it}, materials M_{it}, and services S_{it} based on supply-and-use tables using a standardized product classification.

Unlike the data used in Corderi and Lin (2011) and Inglesi-Lotz (forthcoming), the data used in this study is based on the correct methodology for measuring productivity, and includes additional information on intermediate inputs; a breakdown of intermediate inputs into energy, materials, and services; a breakdown of hours worked by type of worker; a breakdown of investment into various asset types; and a calculation of capital stocks and services using a harmonized methodology. In addition, the data used in this study improves upon the data previously used in Corderi and Lin (2011) by incorporating a longer historical time series.

4. Empirical Model and Estimation Issues

Allowing for both the parameter μ and the rate of return to R&D $\tilde{r}$ in equation (6) to vary by country, we estimate a regression equation of the form:

$$TFPgrowth_{it} = \mu_i + \tilde{r}_i RDint_{it} + \theta_t + \varepsilon_{it}, \quad (8)$$

where $TFPgrowth_{it}$ is the growth rate in TFP for country i at time t and is given by $TFPgrowth_{it} = \dfrac{TFP_{t+1} - TFP_t}{TFP_t}$; $RDint_i$ is the R&D intensity, defined as the ratio of R&D

expenditures to industry value added, in country i at time t;[12] μ_i are country fixed effects; θ_t are year fixed effects; and ε_{it} is the error term, which is assumed to be heteroskedastic (by country) and serially uncorrelated. The parameter of interest is $\tilde{r}_i$, which represents the country-specific rate of return to R&D in energy-related industries for each of our countries.

We use a fixed effects rather than random effects panel estimation model since we believe that time-invariant country-level unobservables that may affect TFP growth, such as the country's natural resources, human capital, and regulatory environment, can be potentially correlated with R&D. The possibility of correlation between time-invariant country-level unobservables and the regressors has also been suggested by Jones and Williams (1998).

We estimate equation (8) using ordinary least squares (OLS). We acknowledge the possibility of heteroskedastic errors and calculate standard errors using White's robust error variance estimation procedure.

Before proceeding to the estimation results, several estimation issues should be addressed. First, although measuring the rate of return through intra-industry spillovers can be problematic due to measurement error at the firm level, aggregation to the industry level helps mitigate these measurement problems.

Another concern is that the error term ε_{it} may be correlated with the regressors, which would lead to inconsistent estimates. The disturbances capture idiosyncratic factors that affect measured productivity. Some could be country specific, for example representing countries that have more inter-industry spillovers; others might be common to all countries such as shocks

[12] Following equation (6), in which the TFP growth rate is a function of the contemporaneous R&D intensity, we regress the TFP growth rate on the contemporaneous R&D intensity rather than the lagged R&D intensity, where the TFP growth rate is given by $TFPgrowth_{it} = \frac{TFP_{t+1} - TFP_t}{TFP_t}$.

affecting OECD countries. To address the issue of correlation between the regressors and the error term, we include country fixed effects to capture any unobserved characteristics of countries that are constant over time.

5. Estimation Results

Table 3 presents estimates of the rate of return to research and development by country for the energy-related products manufacturing industry. Table 4 presents estimates of the rate of return to research and development by country for the electricity, gas, and water supply industries. Robust standard errors are reported in parentheses.

For our benchmark specification, we use R&D data from the Analytical Business Enterprise Research and Development STructural ANalysis (ANBERD-STAN) database and we calculate TFP for the United States using the North American Industry Classification (NAICS) classification; this case corresponds to specification (1) in Tables 3 and 4.

In addition to our benchmark specification, we also run several alternative specifications for robustness. Specification (2) uses the Standard Industrial Classification (SIC) classification instead of the NAICS classification to calculate TFP for the United States. Specification (3) drops countries with missing data. Specification (4) uses R&D expenditure data from the ANBERD-STAN database instead of R&D intensity data as the measure of R&D.

5.1 Benchmark results

According to the results of the benchmark specification in specification (1) of Tables 3 and 4, the estimates of the rates of return to R&D that are significant at a 5 percent level are positive, which is consistent with our original hypothesis about the existence of intra-industry spillovers and a positive rate of return.

As far as the energy-related products manufacturing industry is concerned, France and Finland are the only countries with statistically significant estimates. France has a rate of return of 11.9 percent and Finland has a return of 5.1 percent.

For the electricity, natural gas, and water supply industries, the results show statistically significant estimates for France and the Netherlands. France has a rate of return of 10 percent and the Netherlands has a return of 18.5 percent.

5.2 Robustness

The estimates of the rate of return to R&D by country from our alternative specifications are presented in specifications (2) to (4) in Tables 3 and 4. The rate of return estimates for the energy-related products manufacturing industry are consistent with the benchmark results. Estimates for France and Finland are significant in alternative model specifications, with rates of return similar to those of the benchmark specification.

For the electricity, natural gas, and water supply industries, the results show positive and significant rates of return for Netherlands and France in alternative model specifications, a result which is consistent with the benchmark results.

TABLE 3: Rates of Return to R&D for the Energy-Related Products Manufacturing Industry

	Dependent variable is growth rate of total factor productivity			
	R&D intensity			R&D expenditures
	Benchmark	SIC	No missing data	
	(1)	(2)	(3)	(4)
Australia	1.984	1.969	1.786	2.92
	(4.774)	(4.760)	(4.844)	(1.71)
Belgium	-2.409	-2.417	-2.263	-1.54
	(1.316)	(1.316)	(1.263)	(1.67)
Canada	0.573	0.595	0.607	-0.021
	(0.747)	(0.733)	(0.729)	(0.87)
Czech Republic	-23.322	-23.247		0.25
	(42.142)	(42.084)		(2.11)
Finland	5.114 *	5.113*	5.086*	7.71
	(2.283)	(2.254)	(2.242)	(9.36)
France	11.967 **	11.995**	12.066**	3.53**
	(2.985)	(2.972)	(2.966)	(1.04)
Germany	-7.622	-7.551	-7.461	-4.26
	(9.036)	(9.002)	(8.839)	(3.56)
Hungary	-24.269	-24.057		-0.15
	(18.914)	(18.969)		(0.10)
Italy	2.486	2.510	2.150	-0.03
	(15.216)	(15.242)	(15.026)	(3.38)
Japan	3.118	3.383	3.786	-0.001
	(7.440)	(7.139)	(7.006)	(0.002)
Korea	0.272	0.340		-0.0001
	(8.842)	(8.744)		(0.001)
Netherlands	-0.123	-0.106	-0.087	-1.81
	(1.129)	(1.123)	(1.105)	(2.43)
Spain	6.238	6.143	6.743	5.82
	(12.884)	(12.860)	(12.852)	(5.47)
Sweden	1.206	1.243		2.80*
	(4.523)	(4.549)		(1.39)
United Kingdom	1.014	0.984	0.905	0.86
	(1.447)	(1.406)	(1.393)	(0.59)
United States (NAICS)	1.299		1.436	-0.06
	(1.784)		(1.752)	(0.08)
United States (SIC)		2.214		
		(4.571)		
Country Fixed Effects	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y
Observations	281	281	281	276
R-squared	0.20	0.20	0.14	0.19

Notes: Robust standard errors in parentheses. Significance codes: * 5% level, ** 1% level. R&D intensity in (1) to (3) is defined as the ratio of R&D expenditures to industry value added. R&D expenditures in (4) are in units of 10^9 million 2000 $ U.S. constant PPP.

TABLE 4: Rates of Return to R&D for the Electricity, Natural Gas and Water Supply Industries

	Dependent variable is growth rate of total factor productivity			
	R&D intensity			R&D expenditures
	Benchmark	SIC	No missing data	
	(1)	(2)	(3)	(4)
Australia	-1.038	-0.988	-0.781	-0.13
	(3.379)	(3.402)	(3.354)	(0.24)
Belgium	-5.770	-5.981	-5.652	-0.87
	(3.322)	(3.339)	(3.229)	(0.57)
Canada	-5.410	-5.218	-5.457	-0.24
	(4.695)	(4.717)	(4.576)	(0.28)
Czech Republic	-6.504	-6.359		-0.06
	(22.334)	(22.320)		(0.24)
Denmark	-8.677	-8.451	-9.926	-0.41
	(19.523)	(19.503)	(18.797)	(0.71)
Finland	1.195	1.193	1.116	0.86
	(1.325)	(1.330)	(1.308)	(0.90)
France	10.046 **	9.999 **	9.750 **	0.30*
	(3.336)	(3.334)	(3.274)	(0.14)
Germany	-11.218	-10.714	-12.012	-0.55
	(16.629)	(16.590)	(16.046)	(0.58)
Hungary	11.942	12.340		0.03
	(13.710)	(13.744)		(0.05)
Italy	-4.205	-4.027	-4.447	-0.25
	(4.226)	(4.198)	(4.140)	(0.21)
Japan	-14.940	-14.592	-15.126	-0.0009
	(11.529)	(11.469)	(11.400)	(0.0008)
Korea	1.232	1.318		0.0001
	(2.168)	(2.176)		(0.0003)
Netherlands	18.537*	18.191	18.604 *	3.71*
	(9.339)	(9.315)	(9.192)	(1.56)
Spain	1.460	1.576	1.076	0.16
	(4.540)	(4.507)	(4.430)	(0.36)
Sweden	-2.618	-2.455		-0.07
	(5.381)	(5.383)		(0.12)
United Kingdom	-0.353	-0.270	-0.537	-0.07
	(1.592)	(1.582)	(1.521)	(0.14)
United States (NAICS)	3.537		2.270	-0.02
	(18.620)		(18.027)	(0.10)
United States (SIC)		15.200		
		(13.028)		
Country fixed effects	Y	Y	Y	Y
Year Fixed effects	Y	Y	Y	Y
Observations	296	296	296	292
R-squared	0.27	0.27	0.24	0.26

Notes: Robust standard errors in parentheses. Significance codes: * 5% level, ** 1% level. R&D intensity in (1) to (3) is defined as the ratio of R&D expenditures to industry value added. R&D expenditures in (4) are in units of 10^9 million 2000 $ U.S. constant PPP.

6. Conclusion

In this paper, we estimate the rate of return to research and development in energy-related industries by analyzing the productivity effects of intra-industry spillovers from R&D expenditures in 16 OECD countries. Our results suggest that the rate of return from R&D is positive, robust, and significant in France (for both the energy-related products manufacturing industry and the electricity, natural gas, and water supply industries), Finland (for energy-related products manufacturing industry) and the Netherlands (for the electricity, natural gas, and water supply industries). Our estimates of the rates of return estimates are robust across alternative specifications.

One possible explanation for the significant and positive rate of return to energy R&D in both Finland and the Netherlands is the small size of their respective energy-related industries. Of the OECD countries in our sample, Finland has the lowest industry value added for both the energy-related products manufacturing industry and the electricity, natural gas, and water supply industries. Similarly, the industry value added in the Netherlands is in the lowest 25th percentile for the energy-related products manufacturing industry and in the lowest 30th percentile for the electricity, natural gas, and water supply industries. It is possible that their rates of return to R&D are positive because rates of return to energy R&D are high when the energy industry is still small, as the effect of R&D investment on total factor productivity growth may be higher when the industry is not very productive.

A second possible explanation for the significant and positive rate of return to energy R&D in both Finland and the Netherlands is that they are conducting a moderate amount of energy R&D. Energy R&D in each of the two countries fall between the 25th percentile and the 57th percentile for both the energy-related products manufacturing industry and the electricity, natural gas, and water supply industries. Our results are consistent with those of Popp et al. (2013), who find that positive spillovers to energy R&D occurs at moderate levels of research activity.

Neither of these explanations apply to France, however, which has very productive energy-related industries and which conducts a high level of energy R&D. Of the OECD countries in our sample, France has the 4th-highest industry value added for the energy-related products manufacturing industry, which includes the manufacturing of nuclear fuel, and the 2nd-highest industry value added for the electricity, natural gas and water supply industries. In terms of energy R&D, France's R&D expenditures are the 4th-highest for the energy-related products manufacturing industry and the 7th-highest for the electricity, natural gas and water supply industries. In this case. France's positive rate of return to energy R&D may result from the large and highly productive nature of its energy-related industries.

Our result that two countries with low levels of energy industry value added (Finland and the Netherlands) and one country with a high level of energy industry value added (France) have positive rates of return to energy R&D while the countries with intermediate levels of energy industry value added do not have statistically significant rates of return to energy R&D suggests that the rate of return to energy R&D may be a U-shaped function of energy industry value added. Our result that France has a positive rate of return to R&D despite its high level of R&D is evidence against diminishing returns to R&D.

A possible explanation for the lack of significant rate of returns in the electricity, natural gas, and water supply industries in countries other than France and the Netherlands is that this sector is often regulated. Such regulation may make it difficult for firms to appropriate the returns to R&D. For example, if firms invest in cost-saving innovation, regulators may ask them to lower prices, so that consumers, rather than the firm benefits from the cost savings.

Previous work estimating rates of return, including Corderi and Lin (2011) and Inglesi-Lotz (forthcoming), use data based on an obsolete methodology for measuring productivity (Jorgenson, 2009) that leads to an upward bias in estimated rates of return. Not surprisingly, when we use the correct methodology for measuring productivity, we find that fewer countries have significant positive rate of returns from R&D than were found by Corderi and Lin (2011).

This paper estimates a lower bound for the rate of return by using the narrowest definition of spillover effects, and opens many possible avenues for future research to expand the possible spillover effects. To the extent that product innovations are created and used in the same industry, intra-industry spillovers would be a good proxy for the social rate of return. However, the energy sector does affect productivity in many other sectors of the economy; hence the presence of inter-industry spillovers is very plausible in the industry studied. Furthermore, the temporal dimension of spillovers might matter as well; in our analysis we focused on contemporaneous effects of technology. In addition, international spillovers are very likely to happen among OECD countries; technological diffusion from R&D leaders is very likely to affect productivity in the rest of the OECD countries' industry through international trade. Finally, we do not account for potential benefits of R&D in technology to reduce the pollution intensity of energy output. Estimating rates of return that incorporate an expanded definition of spillover effects will be the subject of future research.

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Appendix A: Derivation of equation (6) for growth rate in TFP

We derive equation (6) for the growth rate in TFP as follows. First, take the natural log of both sides of equation (3) for TFP:

$$\ln TFP = \mu t + \gamma \ln Z_t \quad . \tag{A1}$$

Then take the derivative of both sides with respect to time *t*:

$$\frac{d \ln TFP}{dt} = \mu + \gamma \frac{d \ln Z_t}{dt}, \tag{A2}$$

which yields:

$$\frac{\dot{TFP}_t}{TFP_t} = \mu + \gamma \frac{\dot{Z}_t}{Z_t}. \tag{A3}$$

Substitute in the equation of motion (2) for *Z*:

$$\frac{\dot{TFP}_t}{TFP_t} = \mu + \gamma \frac{R_t}{Z_t}. \tag{A4}$$

Multiply and divide the second term on the right-hand side by Y_t:

$$\frac{\dot{TFP}_t}{TFP_t} = \mu + \gamma \frac{Y_t}{Z_t} \frac{R_t}{Y_t}. \tag{A5}$$

Calculating the derivative of equation (1) for output *Y* with respect to R&D stock *Z*, one obtains:

$$\frac{dY}{dZ} = \gamma \frac{Y}{Z}. \tag{A6}$$

Substituting equations (5) and (A6) into equation (A5), one obtains:

$$\frac{\dot{TFP}_t}{TFP_t} = \mu + \tilde{r} \frac{R_t}{Y_t}, \tag{A7}$$

which is equation (6).