Fraunhofer ISI Discussion Papers *Innovation Systems and Policy Analysis* No. 72
ISSN 1612-1430

Understanding the macroeconomic Effects of public Research: an Application of a Regression-microfounded CGE-model to the Case of the Fraunhofer-Gesellschaft in Germany

Allan Grant, Gioele Figus, Torben Schubert

Karlsruhe, February 2022

Responsible for content

Allan Grant, Department of Economics, University of Strathclyde, Glasgow, UK
Gioele Figus, Department of Economics, University of Strathclyde, Glasgow, UK
Torben Schubert, Fraunhofer ISI, Karlsruhe, Germany and CIRCLE, Lund University, Sweden

Recommended citation

Grant, A.; Figus, G.; Schubert, T. (2022): Understanding the macroeconomic Effects of public Research: an Application of a Regression-microfounded CGE-model to the Case of the Fraunhofer-Gesellschaft in Germany, Discussion Papers Innovation Systems and Policy Analysis No. 72. Glasgow/Karlsruhe: University of Strathclyde, Fraunhofer ISI.

Published

February 2022

Contents

Tables

"No matter how we calculate them, there is little doubt that the over-all social returns on publicly supported technological research have been very high. It is not clear, however, whether or not this fact has any normative implications. I am afraid it has very few. More knowledge than is now at hand is required for prescription."

Zvi Griliches (1958, p. 430)

Abstract

Estimating the economic returns to public science investments has been a key topic in economics. However, while in particular microeconomic approaches have been proposed, only a few studies have tried estimating the macroeconomic effects of public science investments. In this paper, we propose a micro-rooted macro-modelling framework, which combines the strength of an econometric causal identification of key effects with the power of a Computable General Equilibrium (CGE) framework, and provides additional economic structure of the estimates allowing us a fine-grained sectoral differentiation of all effects. Applying our approach to the German Fraunhofer-Gesellschaft, the world's largest publicly funded organization for applied research, we show that macroeconomic returns are - irrespective of econometric specification - a high multitude of the original investment costs. In specific, the activities by the Fraunhofer-Gesellschaft increase Germany´s GDP by 1.6% and employment by 437,000 jobs. Our CGE analysis further shows that the effects concentrate in the chemicals, pharmaceuticals, motor vehicles and machinery sectors. The substantial size of our estimated effects corroborate recent macroeconomic evidence on the social returns to innovation.

1 Introduction

Following the insights of the central importance of public science for economic development from various literatures in economics and social sciences (Nelson 1959, Nelson and Winter 1982, Romer 1990, Dosi and Nelson 2010), expenditures for science organizations take significant shares in public budgets in most developed countries. Yet, the significant state investments have also resulted in calls to justify the spending by proving sufficiently high economic returns (Schubert 2009). The increased interest in the returns of science has resulted in a large number of studies gathering econometric evidence particularly on the micro-level of the firm. For example, Robin and Schubert (2013) and Comin et al. (2018) show that collaborating with public science or organizations increases firm productivity. The central problem is that the necessary causal link between investment in public science and ensuing economic returns are easier to establish on the micro-level of e.g. individual firms collaborating with scientific organizations. However, aggregating up from micro to macro-economic effects is fraught with difficulties and at best leads to rough estimations because they neglect the interdependencies between the various markets (Robin and Schubert 2013, Comin et al. 2018). Other authors document the positive effects on firms' innovativeness (Lööf and Broström 2008, Maietta 2015).

Yet, despite the accumulating micro-level evidence of the value of science, precise and causally identified macro-level estimates, i.e. estimates of how important public science organizations are for the overall economy, are very difficult to obtain. A number of studies have used input-output models (Bürgel et al. 1996; Glückler et al. 2015; Kowalski et al. 2012), which try taking stock of accounting data on university expenditures and apply macroeconomic multipliers to them. A severe limitation of these approaches is that the value of public science organizations is reduced to their observable monetary flows while the value of knowledge as the, arguably, most relevant output of public science is not at all considered (Glückler et al. 2015, Schubert and Kroll 2015). Inspired by Goldstein and Renault (2004) and Carree et al. (2014), Schubert and Kroll (2016) have recently proposed a regional-econometric approach, which circumvents measuring the value of knowledge by relying on robust statistical associations to infer to causality. Applying the model to German NUTS-III regions, they found that universities have considerably positive effects on GDP and, at least in the longer run, also on employment. While these findings are valuable, the methodology hides the mechanisms translating investments in public science into macroeconomic returns behind a regression equation and thus resembles a black box. Thus, while it is useful to obtain information on the overall size of the effect of universities on economic size, the regional or macro-economic regression approaches may hold few normative implications for improving science policy. Important questions, such as how science affects the economy or which sectors of the economy it affects mostly, remain difficult to answer.

To achieve the level of detail necessary to answer arguably more relevant policy-questions, we propose a combined micro-macro modelling approach. Here we estimate the causal effects of public science for applied research from a regional econometric approach similar to Schubert and Kroll (2016) and use the resulting effects to feed into a computable general equilibrium (CGE) model for Germany. It captures the contribution of the Fraunhofer-Gesellschaft to key macroeconomic indicators and productive sectors. This combined micro-to-macro approach has the advantage that it retains econometric rigor with respect to the identification of causal effects but allows integrating detailed knowledge about how these effects propagate through the overall economy. It therefore contributes to opening up the black box of the econometric approach as a stand-alone whilst providing solid evidence for macroeconomic simulations.

Focusing on the German Fraunhofer-Gesellschaft, - which is with 74 individual institutes and approximately 29,000 employees, the world's largest publicly funded organization for applied research - our approach documents considerable effects even in the most conservative of settings. Specifically, we show that the GDP annual contribution of the Fraunhofer-Gesellschaft is approximately 1.6% of the German economy. Furthermore, it induces investment effects of € 15.2 bn. and creates 437,000 jobs across the economy. We find that these are mostly in motor vehicles, computer and electronics, machinery, chemical and pharmaceutical industries. In our approach, results are robust to controlling for endogeneity concerns with the regressions as well as concerns about modelling in the CGE-approach. In particular, we control for unobserved heterogeneity by using fixed effects, selectivity biases by using entropy-weighting, simultaneity by using dynamic panel data estimators as well as non-stationarity in the time-series by implementing a cointegration analysis. On the CGE-model, we consider a large number of modelling alternatives.

We contribute to the literature with both methodological improvements and novel results. On the methodological side, we propose a solid micro-to-macro approach, which makes use of both regression techniques with a CGE-approach to estimate the economic returns to public science investments. The proposed approach combines the ability to establish causality by appropriate econometric approaches with the ability to exploit the structural details of macro-economic models, CGE in particular. In terms of results, we corroborate recent findings by amongst others Jones and Summers (2020) and Schubert and Kroll (2015) showing that the returns to science and innovation are often a high multitude of the original investments and typically much higher than other types of state investments. Third, we provide detailed insights into the sectoral composition of the returns in terms of various macroeconomic indicators, which regular regression approaches are unable to deliver.

2 Background and literature review

2.1 The Fraunhofer-Gesellschaft

The Fraunhofer-Gesellschaft is a public non-profit organization focusing on applied research. It was founded in 1949 with the strategic intent to support and rebuild the German industrial sector after the Second World War. In particular, it was intended to bridge the gap between science and industry by bringing scientific results to commercial application. Despite its worldwide size and reputation today, it remained limited in size and somewhat marginal for a long period after its foundation. In 1959, it consisted of nine institutes with a budget that today is worth less than € 10 million . The tides for extra-university research in general, and for the Fraunhofer-Gesellschaft in particular, however, began to turn in the 1960s. Following the advice of the Research Council (a semi-public advisory organization), in 1973 the German parliament officially accepted the so-called "Fraunhofer-model" forming the basis of the still continuing growth of the Fraunhofer Society.

Currently, Fraunhofer is the largest non-profit organization for applied sciences in the world. In 2020 it commanded a budget of € 2.8 billion (Fraunhofer-Gesellschaft 2021). FhG is organized as a private registered association ("eingetragener Verein, e.V.") and receives base funding amounting to roughly 30% of its total budget (90% from the federal government and 10% from the regional government where the respective institute is located). The Fraunhofer Society comprises 72 research institutes located all over Germany. The institutes focus on different topics mostly in the field of engineering and natural sciences, though a few institutes, such as Fraunhofer ISI and Fraunhofer IAO, exist which are more related to social sciences and economics. FhG's mission makes it the natural organization to study the magnitude of scientific knowledge transfer to private firms. In 2020, approximately a quarter of its revenue came from industry, which is by far larger than for universities, where the total share of third party funds is less than 4% (Destatis 2020).

2.2 The social returns to R&D

Returns on investment in research have long been an important topic in empirical economics. A substantial number of papers have analysed the private and social returns to R&D performed by firms. While this type of R&D differs from public R&D spending inside universities because of the presumably higher degree of basicness and the associated higher spillovers, empirical results of firm-level R&D are still interesting because they give a first point of comparison about reasonably expected effect sizes. Hall et al. (2010) provide a comprehensive literature review of econometric studies trying to estimate the private and social internal rates of return (IRR) of R&D spending. Their results indicate that, although often imprecisely measured, the social IRR is often 100% and thus considerably high. A recent paper by Jones and Summers (2020) tries to estimate different measures of social returns associated with R&D based on a variety of different assumptions. This paper is particularly relevant for our study first because it provides estimates on the macroeconomic level, which comes closer to our questions. Second, beyond the IRR it also provides estimates of the benefit-to-cost-ratio (BCR), which is at least roughly comparable to our key figures. Thus, the results by Jones and Summers (2020) provide descriptive points of reference to judge the plausibility of our findings. In specific, the authors show that the social BCR is highly dependent on assumptions, discount factors, inflation biases and time lags between R&D and returns in particular. However, even under very conservative (extreme) assumptions, the returns on R&D are at least four times larger than the initial investment costs. Under plausible assumptions, the BCRs range approximately between 10 and 25. While these results provide some initial guidance, the returns on private R&D and spending on public research may still differ. In the next subsection, we will review the various literatures, which have tried to estimate the economic value of public research.

2.3 The economic value of public research

Previous scientific analyses of the economic value of public research have largely focused on universities. Most analyses have used input-output or Keynesian multiplier approaches when measuring demand-oriented, tangible effects illustrated by monetary expenditure flows such as student consumption expenditure, university investment expenditure, etc. (for example, Bürgel et al. 1996; Glückler et al. 2013; Kowalski et al. 2012). These studies document an overall positive effect, which is usually low with GDP-multipliers hovering between 1.5 and 2. While such multipliers are well in the range of the returns associated with other public investments into infrastructures, this approach ignores effects that are usually associated with intangible knowledge output (Glückler et al. 2015). However, providing intangible knowledge-associated outputs are not only an inherent task of research organisations but, arguably, the most significant drivers of the economic effects of scientific institutions (Florax 1992, Schubert and Kroll 2015). In particular, Pastor et al. (2018) and Sudmant (2009) argue that the gap between investments into public research and investments into physical infrastructure is that physical investments only have a static effect on the economy while public research has also a dynamic effect.

Measuring dynamic effects is considerably more difficult because of the inherent unobservability of knowledge. Not surprisingly, most analyses have used econometric techniques to infer to the effects by exploiting statistical associations. One strand of the literature has focused on firm level data. Examples include Lööf & Broström (2008), Maietta (2015), Robin and Schubert (2013) and Comin et al. (2018), who document robustly positive effects on public research, on firm innovation and productivity. While these results are suggestive of the considerable dynamic effects channelled through the knowledge links between firms and science, inferring to the overall macro-economic impacts, though not impossible, is still ridden with conceptual difficulties. In particular, Robin and Schubert (2013) and Comin et al. (2018), who also derive macro-economic productivity estimates from their firm-level regressions, stress the importance of macro-economic substitution and readjustment effects resulting in interdependencies between producer, consumer, credit and labour-markets as well as equilibrium processes. Since such interdependencies remain unaccounted for in micro-econometric models, they therefore caution against the overinterpretation of their macro-economic estimates.

Only a few studies have so far addressed the shortcomings resulting from the reliance on firm-level data, implying that macro-economic estimates of the importance of public science remain scarce. Recently, a few studies have appeared that try to estimate the macro-economic effects, which rely on macro-econometric approaches. The earliest attempts are probably due to Goldstein and Renault (2004) and Goldstein and Drucker (2006) who use metropolitan-level economics with university data for the US. They find amongst others that in particular smaller city-areas benefit by suggesting that universities may anchor agglomeration economies. A similar approach is followed by Schlump and Brenner (2010) for Germany. A limitation of these works is that they did not deliver precise macro-economic estimates of the value of public research but remained at a more abstract level. In an attempt to overcome this limitation, Schubert and Kroll (2013; 2016) extended the methodology put forward by Goldstein and Drucker (2006) to determine the effects of regional higher education, including knowledge-based or supply-oriented effects, using statistical methods from panel data econometrics. Schubert and Kroll (2013) have, in particular, classified the effects on regional GDP per capita as significant, with an annual effect of approximately €190 billion for Germany as a whole, which corresponded to roughly 10% of total German GDP. Since then, a selected number of additional macro-econometric analyses have appeared also relying on econometric techniques to estimate the macro-economic effects. Pastor et al. (2018) using growth-accounting approaches provide evidence that universities account for roughly 11% of GDP in the European Union, which although using a different methodology is remarkably similar to the figures obtained by

Schubert and Kroll (2013). A further result by Valero and van Reenen (2019) uses global historic data covering 78 countries from 1950 to 2010 and found that a 10% increase in the number of universities increased GDP per capita later on by 0.4%.

Indeed, the existing research shows that a number of macro-econometric techniques have been fruitfully applied to estimate the overall value of public research. The literature, however, still displays two important gaps. First, most research has focused on universities with little attention to extra-university public research organizations (an exception is Comin et al. 2018). Although it may seem tempting, directly inferring from the substantial and positive results associated with universities to extra-university organizations may be misleading. An important reason is that the research by many extra-university research organizations is considerably more applicable than the research conducted by universities (Toole et al. 2015). On the one hand, this may imply that the research is closer to the market and therefore easier to absorb for firms. On the other hand, the lower degree of basicness may be associated with lower degrees of knowledge-spillovers. It therefore remains unclear, as to whether the results for universities are indicative of expected positive effects for extra-university public research organizations. A second limitation of purely macro-econometric approaches is methodological. In particular, by being purely statistical, little economic structure is implied in the models going beyond the structural regression equation. In consequence, most macro-economic complexities such as substitution effects, market interdependencies, sectoral propagation effects or dynamic adaptation are not modelled explicitly and are therefore lost. The low degree of economic complexities implied by a regression equation may, arguably, be less problematic for obtaining estimates of the size of the overall effect. However, they severely limit the ability to say something useful about the transmission channels and therefore the obtained estimates retain a black-box character. The introductory reference to Griliches (1958), who argues that being assured about the robustly positive economic effects of public research holds few, if any, prescriptive implications and is therefore pertinent even in the most recent works in the field more than 60 years later.

In the following, we will therefore propose a methodology that fruitfully combines the empirical rooting of a macro-econometric approach with a subsequent macro-economic CGE-based model. This ex post imposes more economic structure and therefore allows us to derive more detailed knowledge of the transmission channels between firm-impact and impact across the macro economy, and therefore contributes to opening up the "black-box"..

3 Methodology and data

3.1 The micro-to-macro approach

We analyse the macroeconomic impact of Fraunhofer by developing and applying a CGE model of the German economy in combination with an econometric estimation of the direct impacts of Fraunhofer on the German economy.[1] This method, which can be characterized as 'micro-to-macro' allows us to capture the nature and size of the direct impact that research institutions have on a given economy via the econometric estimation, and to observe the secondary impacts of these via CGE simulations. To do this, the CGE model compares two states of the economy, with and without a policy intervention. In this paper, we are interested in comparing the German economy with and without Fraunhofer's contribution. Past applications of a related approach, such as Gieseke and

1 See appendix A for a full description of the model.

Madden (2006) and Hermansson et al (2014, 2017a, 2017b) have focused on the impacts that higher education institutions have on regional economies and found large impacts on labour productivity and economic growth. However, these studies are limited in that they rely on estimated econometric impacts drawn from the literature.

Within our model, we run heterogeneous exogenous demand shocks that match the production-increased econometric-informed impact that spending of Fraunhofer's budget has on German GDP purposely estimated for our analysis by econometric estimation. In response to these shocks, the economy will adjust to a new counterfactual macroeconomic equilibrium. The contribution of Fraunhofer´s activities on key economic variables, such as investment, employment, and government revenue, is estimated as the difference between the initial and the new equilibrium.

In the initial baseline equilibrium, the CGE model is calibrated using Input-Output (IO) accounts for Germany in 2016 (Destatis, 2020b) augmented with national accounts from the German Institute for Statistics (Destatis, 2020a) to form a Social Accounting Matrix. Crucially, this allows the CGE model to consider the contribution of Fraunhofer not only on the aggregated macroeconomic level, but also to trace the ramifications of these impacts on different industries within the German economy.

To estimate the size of these exogenous demand shocks and hence to define our counterfactual simulations, we estimate the economic contribution that 1€ spending on the Fraunhofer budget generates for the economy. This is discussed in detail in the following section. We multiply this estimate by the total Fraunhofer budget for 2016. This figure is then used to calibrate the counterfactual scenario in the CGE model.

The structure of the CGE model is based on Lecca et al. (2014) and Devarajan and Go (1998). It represents Germany as an open economy that trades goods and services domestically and with the rest of the world. Production is represented by modelling competitive, profit maximizing firms that use a combination of capital, labour and intermediate inputs, produced both domestically and imported to produce a single homogeneous output. This is represented using a nested constant elasticity of the substitution production function (Equations A.14-A.18), where the elasticity of substitution is set to 0.3 following a recent estimation for Germany by Mućk, J. (2017).

International trade follows the so-called Armington (1969) assumption whereby domestically produced and imported intermediate goods are imperfect substitutes (Equations A.19-A.21). The trade elasticity of substitution is set to 2.7 following Bajzik et al. (2019).

A single labour market with perfect labour mobility is imposed, in which we assume that wages are subject to a wage bargaining function whereby the real take-home wage is inversely related to the unemployment rate in Germany (Equation A.11). This follows the econometrically estimated model in Blanchflower et al. (1994).

The model is used to balance demand and supply starting from the assumption that the economy is in long-run equilibrium. Following a disturbance, such as that represented by additional demand related to activities via Fraunhofer, the model solves for comparative statics equilibria. The short-run equilibrium is represented by a situation where capital stocks are fixed (Equation A.64). Subsequently, capital stocks adjust via investment (Equations A.43-A.46) until a new long-run equilibrium is reached, where the value of additional investment is equal to their cost and investment only cover for depreciation (Tobin, 1969, Hayashy 1982).

3.2 Parameterization of the CGE model simulations

3.2.1 The data sources and the model

The CGE model simulations are parameterized based on the production-increasing effects of Fraunhofer based on a regional econometric model. It aggregates regional macro-indicators such as GDP and Fraunhofer indicators on the NUTS3 level. To generate the necessary data, two basic data sources were used. First, all macroeconomic regional data was collected from the online sources of the Federal Statistical Office (DESTATIS). All Fraunhofer-indicators were taken from the SIGMA database - an internal database covering key information on each Fraunhofer institute. The SIGMA-database is provided at the institute-level and not directly at the NUTS3-level. However, it contains postal codes for each institute, which allows aggregating the relevant Fraunhofer-indicators at the NUTS3 level using publicly available concordance tables between postal codes and NUTS-regions. The finally merged dataset covers the 15-year period from 2003 to 2017 and therefore extends the time coverage of the previous study by three years. In the cross-sectional dimension, the dataset covers 400 NUTS 3 regions, implying that in total 6,000 time-year observations are included.[2]

Based on the derived panel data, econometric methods were used to identify the systematic relationships between regional Fraunhofer activity and regional economic core variables. Generically, we use the following structural model:

$$\frac{GDP_{it}}{population_{it}} = \beta \frac{Fraunhofer_{it}}{population_{it}} + z_{it}\delta + u_{it} \tag{1}$$

where (1) relates to an indicator of per capita Fraunhofer activities, $Fraunhofer_{it}$, to GDP per capita, z_{it} represents a vector of regional controls and u_{it}, a structural error term. Our main interest is in the estimate of the coefficient β, which measures the GDP value of an additional one-unit increase in $Fraunhofer_{it}$ in monetary terms..

3.2.2 Identification strategy

A key issue in estimating β in equations (1) is whether the association is correlative or whether it represents causal effects. Several mechanisms pertinent to the economic effects of Fraunhofer may complicate obtaining causal estimates. In specific, problems may result from unobserved heterogeneity, selection based, locational choice and non-stationarity.

Unobserved heterogeneity occurs if regions differ in characteristics that are not captured by explicitly included regional control variables. As a default, all models presented in this paper account for time-constant unobserved heterogeneity by controlling for fixed effects. While controlling for time constant unobserved heterogeneity accounts for many of the problems inhibiting causal identification, in particular selection biases and locational choice are more complicated to treat properly.

With regard to locational choice, regions hosting Fraunhofer institutes differ substantially from those that do not. Fraunhofer institutes choose to locate in regions that are *a priori* economically stronger, which is likely to be the case given that Fraunhofer institutes cluster in metropolitan areas. Any observed associations between Fraunhofer presence and economic outcomes may then be

---

[2] Any missing values were forward imputed to create a balanced panel.

partly or even completely correlative. In particular, it stands to reason that the association between Fraunhofer activities and regional economic outcomes are overestimated. There are several econometric ways to account for such endogeneity biases. Firstly, if locational choice is determined by observable variables, sample-balancing approaches are useful because they homogenise samples. One convenient way to achieve this is to use entropy-balancing (Hainmueller 2012), which provides an automatic procedure to derive regression weights, thus creating balanced samples which do not differ in key control variables (for example, region size, share of agriculture etc.) anymore.

Secondly, if locational choice depends on unobserved but time varying variables, entropy balancing will not eliminate all the bias resulting from locational choice. In this case, more general types of instrumental variable approaches are needed. Since our dataset and estimation context is devoid of broad natural experiments, we used covariance restrictions to derive instruments as proposed by Arrelano and Bond (1991), Arrelano and Bover (1995), and Roodman (2009), based on Generalized Methods of Moments (GMM) panel data models. The resulting instrumental variables usually do not have an easily identifiable narrative of their exogeneity, but the assumptions necessary for their exogeneity can be tested because the models are typically over identified. Specifically, we run the GMM-type of models that treat the indicator of Fraunhofer activities as endogenous, drop the level equation, and collapse instruments in order not to weaken over identification tests (compare Roodman 2009 for a discussion).

A final issue resulting from our modelling exercise relates to our relatively long panel-datasets, which may cause spurious associations resulting from non-stationarity. Non-stationarity is a time-series feature, which roughly speaking means that the distribution of a variable is not constant over time. In fact, many macro-economic variables such as GDP are increasing over time and in that respect non-stationary. However, regressing non-stationary variables on each other results in spurious regression and biased coefficient estimates. One exception is if the non-stationary variables form a so-called cointegrating relationship - i.e. if there exists a linear combination of them, which is stationary. In this case, dynamic OLS can be used to consistently estimate the long-run relationship between them (Kao and Chiang 2000). With respect to our setting, we will show that both GDP per capita and Fraunhofer activities per capita (as in Eq. 1) are non-stationary but cointegrated. This implies that panel-cointegration regressions can consistently estimate the relationship between the two.

The next subsection briefly presents descriptive statistics on the overall estimation sample. These figures are mainly a point of reference for the reader. However, they do show that regions hosting Fraunhofer Institutes differ fundamentally from those that do not, making the issue of locational choice highly relevant.

3.2.3 Control variables

Beyond the precise estimation techniques, Eq. (1) requires the specification of a vector of observable control variables z_{it}. While potentially a larger number of controls may be of interest, the fact is that most will refer to fairly stable characteristics that do not change much over time. The inclusion of fixed effects is likely to account effectively for regional differences. Nonetheless, a selected number of key controls appears to be crucial. Most importantly, the in size and budget dominating public science players are universities. We therefore include the number of regional students per capita as a proxy to account for the universities' confounding effects on GDP. Secondly, we include the share of agricultural employees in the region to control for the degree of urbanization. Third, we include the number of employees in high-tech sectors in order to measure the degree to which technologically advanced sectors are present in the region. Overall, the results appeared to be reasonably robust with respect to other choices of control variables.

4 Results

4.1 Parameterization

4.1.1 Baseline results

The main descriptive results for the key variables used in this section are presented in Table 1 below, where the columns on the left show the results for the full sample, and the columns on the right show the results for those regions with Fraunhofer activities. The average NUTS 3 region has a GDP per capita of €30,423, and annually applies for 194 patents. The regions hosting Fraunhofer Institutes differ in this respect by showing GDP per capita values of €38,544, with patent applications amounting to 399. Whether these differences reflect any causal effects of Fraunhofer activities remains unclear because the regions also differ in other characteristics. In total, the average region has 203,593 inhabitants and a share of agricultural employment of 2.3%. Regions hosting Fraunhofer Institutes differ substantially, with a population of 369,778 and a share of agricultural employment of 0.92%. Overall, our results show that Fraunhofer Institutes cluster in regions that have higher economic power, are larger, less rural and are more patent intensive. This implies that accounting for heterogeneity between regions and for locational choice may be highly relevant in identifying causal effects.

Table 1: Descriptive statistics for the regions

	All regions			Regions with Fraunhofer Institutes		
Variable	**Obs**	**Mean**	**Std. Dev.**	**Obs**	**Mean**	**Std. Dev.**
GDP per capita	6000	30423.8	13721.3	795	38388.20	17879.6
FhG-budget (Euro) per capita	6000	16.0454	82.6841	795	117.73	198.611
FhG-budget (Euro)	6000	4000000.0	17000000.0	795	30000000.0	390000000.0
Students per capita	6000	0.0098	0.0332	795	0.04	0.04844
Population	6000	203593	231676	795	369778.0	491147
Share agricultural employees (%)	6000	2.34413	2.03282	795	0.9235	1.2651
HT-employees	6000	1140.1	545.877	795	1158.9	569.861

In the next subsection, we present the main regression results for equations (1) and (2), where we first start with the GDP results and then continue with the patent results.

Table 2 below shows the main results based on fixed effects (FE)-regressions for GDP. The column on the left uses contemporaneous values of the total Fraunhofer budget. The column on the right repeats the same regressions but use the Fraunhofer indicators lagged by one period, in order to allow for lags between cause and effect.

Table 2: Baseline results (GDP per capita; FE-regressions)

	(1)	(3)
	FE Lag(0)	**FE Lag(1)**
FhG-budget (Euro) per capita	21.4293***	
	(8.86)	
L.FhG-budget (Euro) per capita		21.6065***
		(7.54)
Students per capita	-3051.7371	-2535.8210
	(-1.38)	(-1.15)
Share agricultural employees (%)	-275.8619*	-314.1583*
	(-2.13)	(-2.31)
HT-employees	5.2004***	5.1153***
	(6.09)	(5.73)
Constant	30857.0587***	31063.8180***
	(27.64)	(26.55)
Year dummies	Yes	Yes
Observations	6000	5600
R^2	0.680	0.668

t statistics in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Overall, the results are insensitive to the lag structure. Column 1 and Column 2 show that increasing the Fraunhofer budget by €1 is associated with an increase in GDP of between €21.42 and €21.60.[3] For the parameterization, we will focus on the contemporaneous estimate of €21.42, although we also redo the analysis for the most conservative estimate.

4.1.2 Robustness checks

We performed a number of robustness tests to analyse inasmuch the results are affected by modelling choices. A particular concern are endogeneity biases, resulting from e.g. endogenous locational choice. Columns 1 and 2 in Table 3 below present the results for the GMM-type Arellano-Bond (AB) estimations and the entropy-balancing approach. While the size of the coefficients differ between the different methodologies, the coefficients remain significantly positive, not falling below a 1:19 ratio for the total Fraunhofer budget, and 1:2.98 million ratio for the Fraunhofer researchers.

[3] The levels interpretation is equivalent to the per capita interpretation because dependent and explanatory variables use the same normalisation.

Table 3: Robustness checks (GDP per capita)

	(3)	(5)
	GMM - dynamic panel	**Entropy balancing**
FhG-budget (Euro) per capita	30.4535***	19.1350***
	(11.87)	(4.68)
Students per capita	5620.3078	-4513.5180
	(1.50)	(-1.29)
Share agricultural employees (%)	-248.2824*	890.6073*
	(-2.38)	(2.54)
HT-employees	1.0987	4.8122*
	(0.60)	(2.08)
Constant	NA	17223.8018***
		(5.55)
Year dummies	Yes	Yes
Observations	5600	6000
R^2	NA	0.967
Hansen-overid pval	0.38	NA

t statistics in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

All models so far have been applicable under regular panel-data settings. In particular, they are reliant on fixed-T-large-N asymptotes, which imply that all-time series are stationary. The fixed-T-large-N framework is clearly a reasonable choice because our cross-section dimension is substantially larger (N=400) than our time-series dimension (T=15). At the same time, it is accepted that several of our variables (in particular, GDP per capita) are usually found to be non-stationary. Since Fraunhofer budgets and employee figures have been continuously on the rise in the last two decades, it stands to reason that these time series may also be non-stationary. It is well known that regressing a non-stationary variable on another one produces spurious regression results (Granger et al. 1974). Differencing (integrating) time series is an appropriate way to make them stationary.

However, if time series are cointegrated, the quick-fix solution of regressing the integrated time series on one another is consistent but the coefficients is often undesirable because of poor identification in finite samples. Conceptually, cointegration implies that the cointegrated variables are bound together by an economic relationship in the long run.[4] Since Fraunhofer budgets have grown, based on the Pact for Research and Innovation by a fixed rule, which was arguably fiscally implementable because of a growing economy, there are good reasons to suspect that GDP, patents and Fraunhofer activities are not only non-stationary but also cointegrated. Therefore, we probed our results using cointegration analyse.

Table 4 below presents the relevant test statistics needed to corroborate that the conditions, under which cointegration analysis is applicable, are met. In the left column we see that the null hypothesis of non-stationarity can be rejected for any of the time series. The inverse normal test statistic is not

[4] Technically, cointegration means that for j non-stationary variables of the same integration order, there exists a real-valued vector of length j, such that the linear combination of the variables based on that vector is stationary. That vector is called a cointegrating vector.

significant for any of the relevant variables. In addition, the right column shows that the relevant variables are indeed cointegrated because the null hypothesis of no cointegration is rejected with a high degree of confidence. All tests are fairly general and allow for trend stationarity and a lag-structure of two. Thus, regressions are an appropriate choice to estimate the long-term relationship between Fraunhofer activities and the regional economic outcomes under consideration.

Table 4: Panel unit-root and cointegration tests

	Inverse normal panel unit root stat.	**Panel t cointegration stat.**
Null hypothesis	*All panels have unit roots*	*No cointegration*
GDP per capita	11.4	
FhG-budget (Euro) per capita	2.67	
FhG-budget (Euro)	3.17	
GDP p.c.~FhG-budget p.c.		-15.94***

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

We used the Dynamic OLS estimator proposed by Kao and Chiang (2000), and used one lead and one lag to account for the short-term dynamics, but did not observe changes when allowing for more leads and lags. The results can be found in Table 5 below, and they largely confirm those obtained from the regular panel models presented in the previous section. For all variables and outcomes, the effects are positive and significant. It should be noted, however, that for patents as the dependent variable, the models were not well behaved in their most general form because of singular variance matrices. For these two models, Table 5 presents only restricted versions, which include either a linear time trend instead of year dummies (Column 4) or no time controls (Column 3). In Column 3, we even observed issues due to multicollinearity, which forced us to drop some of the control variables. Overall, the results for the patent regressions should therefore not be overinterpreted.

Table 5: Estimation of the long-run cointegration relationship (Dynamic OLS)

	(1) **Dynamic OLS**
FhG-budget (Euro) per capita	20.9756***
	(4.19)
Students per capita	61223.1824***
	(15.68)
Share agricultural employees (%)	-2517.3495***
	(-8.99)
HT-employees	-0.1467
	(-0.08)
Year dummies	Yes
Observations	4800
R^2	0.861

t statistics in parentheses; $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Nonetheless, for GDP per capita, the models worked well and also corroborate the previous findings to an extent. In particular, Column 1 shows that a €1 increase in the Fraunhofer budget implies a €20.9 increase in GDP, which is very similar to the original results in Table 2 and the entropy balancing in Table 3.

Beyond the results in Table 3 and Table 5, we also performed a number of other robustness tests, which we do not explicitly report here to save on space. First, we re-estimated all models with the number of Fraunhofer scientists as the main explanatory variable. The results were significant in all cases and led also in size to comparable macroeconomic estimates (see next section). Moreover, we differentiated the respective effects of the Fraunhofer budget and researchers by an early (before 2015) and a late (2015-2017) time period. This is to account for the fact that in more recent years Fraunhofer's budgets had increased considerably, which may have potentially influenced results for example by either causing labour market congestions on the negative side or by opening up new business and research opportunities for Fraunhofer. While we do not have a strong prior on the expected direction of the changes over time (if any), our results showed that the macroeconomic effects of Fraunhofer on GDP appeared to increase rather than decrease somewhat over time.

5 Results from the macroeconomic model

5.1 Scenarios

As discussed, the macroeconomic simulations consider a series of counterfactual simulations related to the German economy with and without Fraunhofer by matching the macroeconomic GDP impacts from the microeconomic analysis presented in section 4. To estimate the total size of exogenous demand shocks related to the production-expansion associated with FhG, we assume that the additional FhG budget has a causal impact on the German GDP through increasing the demand for production sectors engaged with FhG. The reason for focusing on the demand side, as opposed to productivity shocks, is that the econometric results provided evidence that the main effect of Fraunhofer on GDP is channelled through changes in demand. In particular, results showed that Fraunhofer activities had a positive effect on GDP and employment simultaneously cancelling out effects on productivity. Specifically, we model the demand-side effect as linear in budget. Thus,

$$\Delta GDP = \gamma B, \tag{2}$$

where ΔGDP is the absolute change in GDP, B is the budget for FhG activities, and γ is the effect of FhG budget on GDP and takes values in the range of €21.13 - €21.67 as shown in Table 2.

From this, we derive two distinct exogenous demand shocks. The first shock, referred to as Scenario 1, simulates the knock-on effect of an increase in GDP corresponding to considering a subset of FhG budget (€410 million) that we can map to specific production sectors, using data provided by Frietsch (2020). This scenario forms the core of our analysis, as we know the underlying sectoral distribution of the corresponding budget. The second shock, Scenario 2, simulates the knock-on effect of an increase in GDP corresponding to the entire 2016 budget (€2,081 million). Scenario 2 is an extrapolation of Scenario 1 because it assumes that aggregate FhG effects are distributed by sector in line with the private sector funding.

Plugging these numbers into equation 3 and dividing the results by the total 2016 GDP, we find that Scenario 1 is associated with a 0.31% GDP increase and Scenario 2 with a GDP increase of 1.6%.

5.2 Simulation results

In this section, we provide aggregate long-run effects on key economic variables for Scenario 1 (private funding) and Scenario 2 (entire budget). In addition, we provide sectoral long-run effects for Scenario 1, as we know the underlying distribution of the budget covered by this shock. This allows us to gauge the macroeconomic impacts of FhG activities and their distribution across sectors of the German economy.

5.2.1 Aggregate effects

The long-run effects of Scenarios 1 and 2 on Employment, Investment and Government Revenue are provided in Table 6. We consider each effect in turn. As expected, the total effects for the entire budget (Scenario 2) are much larger than the effects of the considered private sector funding (Scenario 1).

In 2016 about 43.7 million people were in employment in Germany (Destatis, 2016b). Under Scenario 1, this number increases by 0.21% in our model, creating about 92 thousand additional jobs in the long run. In section 4.2. we analyse the sectoral composition of these jobs. Scenario 2 creates 1.0% additional employment, which equals about 437 thousand jobs.

Next, we consider investment effects. In 2016, there was €634 billion investment into German capital (Destatis, 2016b). Scenario 1 estimates that this rises by 0.45% or €2.85 billion in response to private FhG funding covered. This corresponds to a 2.4% increase or €15.2 billion in Scenario 2. Thus, even the more robust investment effect under Scenario 1 outweighs total FhG funding.

Lastly, we consider the impact of FhG activities on government revenue. Under Scenario 1, government revenue increases by 0.21%, which is about €2.7 billion. The entire budget (Scenario 2) is associated with an increase of 1.1% in government revenue. This corresponds to about €14 billion. These increases are mainly driven by additional taxes on labour (note how the proportionate increase in employment roughly corresponds to the proportionate increase in government revenue) but the government also increases its income from capital taxes. Thus, there appears to be a significant tax multiplier for FhG investment.

Table 6: Estimated effects of FhG private funding and total budget on key economic variables

Variable	Scenario 1	Scenario 2
GDP	0.31%	1.6%
Employment	0.21%	1.0%
Investment	0.45%	2.4%
Government Revenue	0.21%	1.1%

5.2.2 Sectoral effects

In this section, we illustrate how impacts from Scenario 1 are distributed across the 28 sector aggregation of the German economy considered in this analysis.[5] As a reminder to the reader, in this scenario we only consider the €410 million private sector funding portion of the total FhG budget mapped to specific sectors. Assuming that private sector collaboration are good proxies[6] for the industrial pattern of the demand effects, this allows us to estimate where in the economy FhG effects are concentrated.

Table 7 reports percentage changes from the baseline in sectoral investment, employment and value added. As can be seen, most sectors are positively affected by the increased demand driven by Fraunhofer activities. The only exception is a small fall in employment in service sectors such as health, R&D and private services. The overall increase in demand puts upward pressure on wages and, given that in our model labour supply is constrained, employment moves towards those industries that experience the greatest expansion. Note that this does not imply that these service industries contract: the increase in investment indicates that their production becomes slightly more capital intensive to compensate for the increased wages.

Increases in Investment and Employment are concentrated in Chemicals, Pharmaceuticals, Motor Vehicles, Machinery. These are the sectors that typically interact more with Fraunhofer activities and that are most exposed to international trade.

Table 7: Investment, Value Added, and Employment % change from the baseline in Scenario 1

	Investment	Value Added	Employment
Agriculture	1.54	1.17	0.17
Mining and Raw Materials	2.02	1.05	0.64
Oil and Gas (incl. refining)	3.41	2.75	2.01
Metal Products	3.29	2.28	1.90
Iron and Steel Products	4.02	2.99	2.62
Rubber and Plastic	3.94	3.00	2.53
Wood and Paper Products	3.24	2.30	1.85
Ceramics and Stone Products	2.31	1.42	0.93
Chemicals	5.20	4.52	3.78
Pharmaceuticals	**9.01**	**8.61**	**7.54**
Computers, Electronics, and Optical	5.62	4.92	4.19
Electrical Equipment	4.11	3.16	2.70
Machinery	4.69	3.68	3.28
Motor Vehicles	4.34	3.71	2.93
Other Transport Equipment	5.30	4.28	3.88
Other Manufacturing	2.41	1.38	1.03

5 Results for Scenario 2 are qualitatively equivalent, therefore not presented here.

6 These are presented in Appendix B

	Investment	Value Added	Employment
Gas, Water, and Electricity Supply	2.38	1.81	1.00
Construction	2.36	1.57	0.98
Publishing, Media, and Culture	1.95	1.30	0.57
ICT Services	1.65	0.86	0.28
Finance and Insurance	2.26	1.35	0.88
Services for Firms	2.17	1.26	0.79
Research and Development	**0.92**	**-0.16**	**-0.44**
Health Services	1.12	0.18	-0.24
Wholesale and Retail	2.83	1.93	1.44
Transportation Services	2.53	1.66	1.15
Other Services (Private)	2.04	1.55	0.66
Other Services (Public)	1.24	0.17	-0.12
min	0.92	-0.16	-0.44
max	9.01	8.61	7.54

Both the Motor Vehicle and Machinery sectors, employ 1.543 million people in Germany (Destatis, 2016b). Under Scenario 1, employment in these sectors rises by 2.1%, and 1.3% respectively. This corresponds to about 25 thousand additional jobs. There is also significant additional investment in these sectors. Investment in the Motor Vehicle sector rises by 2.2%, while investment in the Machinery sector rises by 1.2%. Employment in Research and Development contracts slightly. There are two main reasons for this linked to the characteristics of our model. Firstly, due to the assumption that the labour supply is constrained, and labour can move from one sector to another, labour tends to move to those sectors that receive a bigger boost. However, should the assumption of constrained labour supply be relaxed, the contraction in employment in these sectors would disappear. Second, in the 2016 IO accounts for Germany used to calibrate our model, this sector only sells output to final demand, thus it does not benefit from selling additional output to other industries, as most of the other industries do. A similar result is found in Other Public Services, due to the sector’s limited interaction with Fraunhofer.

With a way above average innovation-propensity (ZEW 2020), the chemical-pharmaceutical industries are also of critical importance to the German economy. Here, FhG activities create 0.7% additional employment in the chemical industry and 0.6% additional employment in pharmaceuticals. These industries also see an increase in investment of 0.9% and 0.7%, respectively.

6 Discussion and conclusion

The returns to public research have been subject to substantial debate over at least the last seven decades. Yet, estimating them has been fraught with conceptual and methodological problems resulting from limited data availability, threats to causal identification due to endogeneity, and difficulties in identifying the total returns including those having spill overs to other actors. We have proposed a regional macro-econometric approach that deals with many of these problems and shows that our findings do in fact vary depending on the econometric assumptions imposed on the models. However, at the same time, they are remarkably robust in terms of size and in none of our regressions fall short of a BCR of 19. Such a high figure may appear unreasonably large when compared to the often low returns from regular public infrastructure investments often hardly recovering the initial expenditures in terms of returns (Canning and Bannathan 2000, Li and Chen 2013). However, when comparing our figures to macroeconomic BCR estimates of R&D finding plausible values between 10 and 25 (Jones and Summers 2020), our results appear to be in line with related findings in neighbouring literatures.

Our econometric estimates of the returns to spending on public research are interesting in their own right for at least two reasons. Firstly, they show that spending on public research pays off with returns in a magnitude that is difficult to recover from other types of public investment opportunities. In that respect, our findings reinforce claims to the overall value of science investments providing an economic justification for them. Secondly, while indeed some studies exist on the economic returns to public spending on basic research (universities in particular), to date there are only very few studies on the economic value of applied public science organizations (RTOs), Comin et al. (2018) being a notable exception. While one may be tempted to take for granted that findings for universities are applicable also to RTOs, such an assumption may be premature: in particular, universities tend to focus on basic research characterized by substantially higher potential for spill overs. At the same time, very basic research may be much more remote from being implementable in terms of a marketable innovation. Thus, whether and if a given basic research finding will develop any commercial value remains unclear. RTOs, such as Fraunhofer, are often much closer to the needs and demands of private firms and thus may provide a type of R&D output, which provides fewer spill overs but is on the other hand easier to absorb and to commercial by private firms. Our results confirm that the applied research provided by Fraunhofer indeed provides outputs, which exceed their initial investment costs by a multitude. Thus, we provide empirical evidence that beyond the investments in universities, supporting applied research conducted by RTOs is economically highly valuable and thus may provide a goal in its own rights. In Germany, applied public research has, with the Fraunhofer-Gesellschaft having been established as early as 1949, a considerable history. Many countries including Sweden (RISE), the Netherlands (TNO), Finland (VTT), Norway (SINTEF) to name just a few have followed. Yet, until now, almost no comprehensive study of the effects of these investments has been available.

Indeed, while our findings are supportive of public investments into applied research, they also raise an important conceptual question: if it is indeed true that applied research tends to provide fewer spill overs, it is not a priori clear why governments instead of private actors should invest into it. More specifically, if in the sense of Nelson (1959) applied research is not or at least to a much lower degree subject to knowledge spill overs, the private actors may well themselves provide these types of applied R&D activities, in particular if the returns are as high as our results suggest. Our results are subtly at odds with this view, because we highlight both that Fraunhofer activities possess a value that goes beyond what the market would provide on its own as otherwise an absence of Fraunhofer institutes in our sample regions could be easily compensated by private actors. So, if it is not spillovers that credibly justify investments into RTOs, our finding begs the question what other types of market imperfections may prevent the market from rendering services provided by RTOs. In this context, recently Comin (2021) suggested there is a need to move beyond the basic science/applied science dichotomy by admitting that RTOs instead provide research that facilitates diffusion of basic research findings. Moreover, the imperfections preventing socially optimal investments into this type of diffusion-research may relate to much more capability limitations resulting from an often-huge cognitive and institutional divide between basic science organizations such as universities and private businesses. Alternatively speaking, the research results provided by universities may well be commercially valuable for firms, but they are framed and expressed in ways that makes direct absorption difficult. RTOs provide a sort of diffusion-relevant research that intermediates between the purely scientific and commercial world by translating and further developing basic research for commercial application. Because such capability restrictions are likely to exist not only on the side of the firms but also on the side of basic research organizations, innovation systems without RTOs find it often difficult to bridge this capability gap. Thus, overall, our results corroborate the importance of applied public research investments - potentially better labelled diffusion research - provided by RTOs.

Yet, we have highlighted that the importance of a conceptual question of the normative implication of empirically high rates of returns voiced already by Zvi Griliches in 1958. The essence of this question refers to the difficulties to derive any policy-relevant implications going beyond the mere statement that (applied) diffusion research is important, e.g. it is unclear from our results how the balance between diffusion and basic research should shift, or what the overall optimal level of the provided state subsidies should be. In addition, from our econometric results, we know little about the specific content. In essence, the core problem is that the knowledge of a BCR - be it 5, 20, or 40 - does not provide sufficient detail about the effects on the economy. Moreover, it says nothing policy-relevant about the desirability of alternative paths of action. To fill some parts of this gap, we provided more structure to our econometric findings by feeding them into a CGE-model of the German economy, which allows us better to capture the economic effects on different sectors of the economy. From this we learn two important lessons. First, the government revenue generated by the additional economic activities more than compensates for the initial spending in financing the Fraunhofer's budget. Second, industries that interact more with Fraunhofer, and that are typically considered 'knowledge intensive', benefit the most from the stimulus driven by Fraunhofer activities with firms. We also find that industries linked to the supply chains of these sectors benefit from second order effects through the composition of their supply chains delivering further stimuli to the wider economy.

Acknowledgements

The work underlying this project has been supported by funding from the Fraunhofer-Gesellschaft. We acknowledge the contribution of Graeme Roy, University of Glasgow and Anton Knoche, University of Strathclyde, for their input at the early stage of this research, and Rainer Frietsch for his help with the data to parametrise the simulations.

7 References

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The review of economic studies*, *58*(2), 277-297.

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of econometrics*, *68*(1), 29-51.

Bajzik, J., Havránek, T., Irsova, Z., & Schwarz, J. (2019). Estimating the Armington elasticity: The importance of data choice and publication bias (No. 19/2019). IES Working Paper.

Bürgel, H.D., Binder, M., Schultheiß, R. (1996): Die Universität Stuttgart als Wirtschaftsfaktor für die Region Stuttgart. Stuttgart.

Blanchflower D., Oswald J (1994). The wage curve. MIT press

Canning, D., & Bennathan, E. (2000). The social rate of return on infrastructure investments. *Available at SSRN 630763*.

Carree, M., Della Malva, A., & Santarelli, E. (2014). The contribution of universities to growth: Empirical evidence for Italy. *The Journal of Technology Transfer*, *39*(3), 393-414.

Comin, D. (2021): A General Equilibrium Quantification of the Impact of Fraunhofer on the German Economy, unpublished manuscript

Comin, D., Licht, G., Pellens, M., & Schubert, T. (2019). Do companies benefit from public research organizations? The impact of the Fraunhofer Society in Germany. *The Impact of the Fraunhofer Society in Germany*, 19-006.

Destatis (2020a). Sector Accounts - Annual results 1991 onwards - 1991 to 2019. Retrieved from https://www.destatis.de/EN/Themes/Economy/National-Accounts-Domestic-Product/Publications/Downloads-National-Accounts-Domestic-Product/sector-accounts-annual-results-xlsx-5812106.html

Destatis (2020b). VGR des Bundes - Input-Output-Rechnung - Fachserie 18 Reihe 2 – 2016 [Datafile]. Retrieved from https://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Publikationen/Downloads-Input-Output-Rechnung/inputoutput-rechnung-2180200167004.html

Destatis (2020). Monetäre hochschulstatistische Kennzahlen, Fachserie 11, Reihe 4.3.2

Devarajan S. and D. Go, (1998). The Simplest Dynamic General Equilibrium model of an Open Economy. Journal of Policy Modeling, Vol. 20, No. 6, pp. 677–714.

Dosi, G., & Nelson, R. R. (2010). Technical change and industrial dynamics as evolutionary processes. *Handbook of the Economics of Innovation*, *1*, 51-127.

Egeln, J., Köhler, C., Niefert, M., Schliessler, P., Kroll, H., Schubert, T. (2015): Wirkungen der öffentlichen Finanzierung von Wissenschaft und Forschung in Baden-Württemberg auf die wirtschaftliche Entwicklung des Landes, Endbericht zum Projekt. Ministerium für Wissenschaft, Forschung und Kunst des Landes Baden-Württemberg (MWK).

Engle, R.F. Granger, C.W. (1987): Co-integration and error correction: representation, estimation, and testing. *Econometrica,* 55, 251-276.

Florax, R.G.M. (1992): The university: A regional booster? Economic impacts of academic knowledge infrastructure. Avebury, Aldershot.

Fraunhofer-Gesellschaft (2021): Jahresbericht 2020, https://www.fraunhofer.de/de/mediathek/publikationen/fraunhofer-jahresbericht.html

Frietsch, R., Lutz, J., Neuhäusler, P. Schubert, T., Lerch, C., Bethke, N., Rothengatter, O. (2017): *Der Beitrag der Fraunhofer-Gesellschaft zum Deutschen Innovationssystem.* Endbericht zum Projekt, Karlsruhe: Fraunhofer ISI.

Frietsch, R., (2020), The macroeconomics effects of Fraunhofer Gesellshaft, Unpublished Manuscript

Figus, G., Lisenkova, K., McGregor, P., Roy, G., & Swales, K. (2018). The long-term economic implications of Brexit for Scotland: An interregional analysis. Papers in Regional Science, 97(1), 91-115. https://doi.org/10.1111/pirs.12349

Giesecke, J.A., & Madden, J.R. (2006). CGE evaluation of a university's effects on a regional economy : an integrated assessment of expenditure and knowledge impacts. Review of Urban & Regional Development Studies, 18, 229-251.

Glückler, J., Panitz, R., & Wuttke, C. (2015). Die wirtschaftliche Wirkung der Universitäten im Land Baden-Württemberg. *Raumforschung und Raumordnung*, *73*(5), 327-342.

Goldstein, H., Renault, C. (2004): Contributions of universities to regional economic development: A quasi-experimental approach, *Regional studies*, 38, 733-746.

Granger, C.W., Newbold, P. (1974): Spurious regressions in econometrics. *Journal of Econometrics*, 2, 111-120.

Griliches, Z. (1958). Research costs and social returns: Hybrid corn and related innovations. *Journal of political economy*, *66*(5), 419-431.

Grillitsch, M., Schubert, T. (2020): Does the timing of integrating new skills affect start-up growth? *Strategic Entrepreneurship Journal.*

Hayashi F., (1982). Tobin"s Marginal q and Average q: A neoclassical Interpretation. Econometrica, Vol. 50, No.1, pp 213-224.

Hermannsson, K., Lisenkova, K., Lecca, P., Swales, J. K., & McGregor, P. G. (2014). The Regional Economic Impact of More Graduates in the Labour Market: A ‘Micro-to-Macro’ Analysis for Scotland. Environment and Planning A: Economy and Space, 46(2), 471–487. https://doi.org/10.1068/a45326

Hermannsson, K., Lecca, P., Swales, J. K., (2017a) How much does a single graduation cohort from further education colleges contribute to an open regional economy?, Spatial Economic Analysis, 12:4, 429-451, DOI: 10.1080/17421772.2017.1316417

Hermannsson, K., Lisenkova, K., Lecca, P., Swales, J. K., & McGregor, P. G (2017b) The external benefits of higher education, Regional Studies, 51:7, 1077-1088, DOI: 10.1080/00343404.2016.1172062

Jones, B.F., Summers, L.H. (2020): *A Calculation of the Social Returns to Innovation*, working paper No. w27863. Cambridge, MA: National Bureau of Economic Research.

Kao, C., Chiang, M.H. (2000): “On the estimation and inference of a cointegrated regression in panel data”, *Advances in Econometrics,* 15, 179-222.

Kowalski, J., Meyborg, M., Dziembowska-Kowalska, J., Häußling, R., Schaffer, A. (Hrsg.). (2012): Karlsruher Institut für Technologie – Impulsgeber für Karlsruhe und die Region. Online: https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCIQFjAA&url=http%3A%2F%2Fwww.ksp.kit.edu%2Fdownload%2F1000030730&ei=BGRMVemwE4rkUq-WgOAI&usg=AFQjCNFzFKxlhl0U7GsLiCsl1eIYC8ZETQ&bvm =bv. 92765956,d.d24.

Li, Z., & Chen, Y. (2013). Estimating the social return to transport infrastructure: A price-difference approach applied to a quasi-experiment. *Journal of Comparative Economics*, *41*(3), 669-683.

Lööf, H., & Broström, A. (2008). Does knowledge diffusion between university and industry increase innovativeness?. *The Journal of Technology Transfer, 33(*1), 73-90.

Maietta, O. W. (2015). Determinants of university–firm R&D collaboration and its impact on innovation: A perspective from a low-tech industry. *Research Policy*, *44*(7), 1341-1359.

Mućk, J. (2017). Elasticity of substitution between labor and capital: robust evidence from developed economies. Narodowy Bank Polski. Education & Publishing Department.

Nelson, R. R. (1959). The simple economics of basic scientific research. *Journal of political economy*, *67*(3), 297-306.

Winter, S. G., & Nelson, R. R. (1982). An evolutionary theory of economic change. University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship.

Pastor, J. M., Peraita, C., Serrano, L., & Soler, Á. (2018). Higher education institutions, economic growth and GDP per capita in European Union countries. *European Planning Studies*, *26*(8), 1616-1637.

Penrose, R. (1959): The apparent shape of a relativistically moving sphere. *Mathematical Proceedings of the Cambridge Philosophical Society*, 55, 137-139.

Robin, S., & Schubert, T. (2013). Cooperation with public research institutions and success in innovation: Evidence from France and Germany. *Research policy*, *42*(1), 149-166.

Romer, P. M. (1990). Endogenous technological change. *Journal of political Economy*, *98*(5, Part 2), S71-S102.

Roodman, D. (2009). How to do xtabond2: An introduction to difference and system GMM in Stata. *The stata journal*, *9*(1), 86-136.

Schubert, T., Kroll, H. (2013): *Endbericht zum Projekt Hochschulen als regionaler Wirtschaftsfaktor Karlsruhe*. Online: http://www. stifterverband. de/ wirtschaftsfaktorhochschule/regionale_bedeutung_von_hochschulen.

Schubert, T., Kroll, H. (2016): Universities' effects on regional GDP and unemployment: The case of Germany. *Papers in Regional Science*, 95, 467-489.

Schlump C., Brenner, T. (2010): University education, public research and employment growth in regions: An empirical study of Germany. *Berichte zur deutschen Landeskunde*, 84: 115–136.

Sudmant, W. (2009). *The economic impact of the University of British Columbia*. Planning and Institutional Research, UBC. Vancouver: University of British Columbia. Retrieved from

Tobin, J., 1969. A general equilibrium approach to monetary theory. Journal of Money, Credit, and Banking 1, 15–29.

Toole, A. A., Czarnitzki, D., & Rammer, C. (2015). University research alliances, absorptive capacity, and the contribution of startups to employment growth. *Economics of Innovation and New Technology*, *24*(5), 532-549.

Valero, A., & Van Reenen, J. (2019). The economic impact of universities: Evidence from across the globe. *Economics of Education Review*, *68*, 53-67.

ZEW (2020): Branchenreport Innovationen 2020 - Chemische Industrie, https://www.zew.de/publikationen/2020-chemieindustrie