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Modeling R&D spillovers to productivity: The effects of tax credits

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How much stimuli that should be attributed to R&D investments crucially depends on how the benefits of R&D reverberate throughout the economy. An extensive literature has found major spillover effects from R&D investments from one industry to another. Using a macroeconomic model for a small open economy, we analyze how tax credits stimulate R&D through the user cost of capital and how it impacts the economy in general via knowledge flows from R&D capital. We find that a tax credit scheme that lowers the user cost of R&D capital, leads to a gradual increase in aggregate productivity. In the long run, the levels of output, real wages, and consumption are around one percent higher than the baseline.

1. Introduction

R&D is a key driver of economic growth. To spur economic growth, most OECD countries support R&D through various policies such as direct support to R&D institutions, tax credits to support business R&D and support to higher education that supplies vital inputs to R&D activities in all parts of the economy.[1] The benefits of increased R&D not only affect firms that undertake R&D investment; the effects reverberate through the economy via knowledge flows from R&D capital. An important policy question is: how large and economically significant are such spillover effects? Without a credible answer to this question it is hard to motivate policy interventions such as tax credit allowances for R&D investments.

There is an extensive international literature that analyzes inter alia domestic spillovers from R&D and productivity growth; see e.g. Mohnen (1997), Griffith et al. (2004), Coe et al. (2009) and Bournakis et al. (2018). Hall et al. (2010) provide a survey of the literature and find that the social returns on R&D investment are significant, and that the estimates in the literature indicate the existence of significant research spillovers from one industry to another. Lucking et al. (2019) also find positive spillover effects of R&D and that the ratio of social to private return is about 4. Moreover, our study builds on the related literature that analyzes openness and economic growth; see e.g. Andersson (2001), Cameron (2006), Khan (2006) and Bournakis (2012). See also Keller (2004, 2009) for a broader overview of this literature. We complement many of these studies by incorporating the channels from R&D, spillovers and openness to productivity growth into a large-scale macroeconomic model.

Norway introduced a tax credit system for R&D in 2002 (SkatteFUNN) to stimulate R&D investment in the business sector. The basic idea was that the Norwegian business sector did not invest enough in R&D at the time compared to other OECD countries. Stimulating R&D by means of government subsidies in addition to existing support in the form of grants from the Research Council of Norway was expected to stimulate productivity growth in the economy. From a microeconometric perspective, Cappelen et al. (2012) analyzed SkatteFUNN and found that receiving tax credits resulted in the development of new production processes and to new products. For a representative firm with no previous innovation, the probability of introducing a new product for the firm increased by 10 percentage points if the firm cooperated with another firm and by 27 percentage points if it also cooperated with a research institute. Without any cooperation they found no increase in the probability of innovation due to the introduction of the tax credit. Similar results were found for the increase in the probability of process innovation due to the tax credit. These results are indicative of spillovers in the sense that firms that collaborate with other firms and research institutes are

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[1] See e.g. https://www.oecd.org/sti/rd-tax-stats-expenditure.pdf.

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more likely to be successful in their innovation activities. However, this study did not analyze the long-term effects of stimulus to R&D investment and its macroeconomic consequences.

In this paper, we add to the literature that analyses how tax credits to R&D affects the economy by specifying empirically the various channels through which these tax credits can work. First, we estimate the effects of tax credits on R&D investments and the R&D capital stock in various industries. Second, we test if there are spillover effects of R&D on the total factor productivity (TFP) between these industries, including possible international spillovers. Third, we study changes in tax credits to R&D using the empirical results from the previous two steps. To this end, we extend a macroeconomic model of Norway with estimated equations that model total factor productivity (TFP) by industry as dependent on both domestic and international knowledge spillovers and the skill composition of employment. The macroeconomic model we use (KVARTS) has a large input-output core and it allows for the production of multiple products in each sector of the economy; see Section 2 and Appendix A for a brief description of the model or e.g. Biørn et al. (1987) and Boug et al. (2013b) for documentation of earlier versions of the model.

We find that stimulating R&D activities through a 23 percent reduction in the user cost of R&D capital, in line with the introduced tax credit system (SkatteFUNN) for R&D in 2002, leads to a substantial increase in R&D investment in the economy. However, it takes a long time before R&D capital stocks increase and knowledge flows to other industries. As R&D capital stocks gradually increase in the various industries, there are spillover effects both from abroad and from domestic sources. We find sizes of domestic and international spillover effects for Norway that are in line with the aggregate results in Coe et al. (2009) and the literature showing that international spillovers are larger for small open economies, such as Norway, see Keller (2004) and references therein. At the aggregate level, these effects are multiplied further, since productivity gains in the production of intermediate inputs lead to reduced input prices in downstream industries and thus a higher level of aggregate productivity. In the short and medium term, the effects on aggregate output are small and the changes in capital stocks by industry are modest. After a decade, economic output increases and continues to grow so that the GDP level increases steadily. This implies that the output growth rate is permanently higher due to the policy shift. Thus, the balanced budget multiplier is positive and increasing over time due to the spillover effects of R&D. The productivity gain leads to higher real wages and consumption. In the long run, the level of output, real wages and consumption is around one percentage point higher in our R&D tax policy scenario than in the baseline.

Closely related to our analysis for Norway are those in Bye et al. (2009) and Bye et al. (2011), which study innovation policies using a computable general equilibrium model. These studies, however, do not capture the interlinkages between industries attributable to domestic knowledge flows. We extend these studies by utilizing a model in which we can identify the importance of both international and domestic spillovers.

The paper proceeds as follows: In Section 2, we provide a general overview of the KVARTS macroeconomic model and a detailed description of how R&D affects total factor productivity. The data used in the analysis are described in Section 3. Section 4 describes the econometric specification and estimation results and decomposes the contributions from domestic and international channels to aggregate TFP growth. Policy simulations are presented in Section 5. Section 6 provides a conclusion.

2. R&D in the macroeconomic model[2]

The KVARTS macroeconomic model is relatively disaggregated, with an input–output system based on the National Accounts. In the short run, the production level is determined by aggregate demand along the lines of the traditional Keynesian framework for an open economy with inflation targeting. In the longer run, the supply side contributes to determining production through the labor supply and the production structure. The model has been developed continuously since the 1980s, and all its structural equations have theoretical underpinnings. These equations are estimated in blocks (mainly) using a cointegrated VAR framework. Recent documentation of some of the main blocks, such as factor demand, the consumption function, the distribution sector and price-setting behavior, can be found in Hungnes (2011), Jansen (2013), Boug et al. (2021), Boug et al. (2013a) and Boug et al. (2017). As these articles illustrate, the methodology underlying the macroeconomic model entails applying econometric specifications that encompass several economic theories and including in the model only those theories that pass the empirical tests. Bårdsen et al. (2005) provide an overview of the methodology upon which the model is based. In the following, we comment on how R&D, together with other input factors, are incorporated in the macroeconomic model. In Appendix A we describe the other blocks of the model.[3]

2.1. Factor input

The level of production, X, in industry j in period t is given by

$$X_{jt} = TFP_{jt} \times F\left(K^{RD}_{j,t-1}, K_{j,t-1}, H_{jt}, M_{jt}\right) \tag{1}$$

where K^{RD}_{jt}, K_{jt}, H_{jt}, M_{jt} and TFP_{jt} represent R&D capital, fixed capital, labor services, intermediate inputs, and technology for industry j. The production function F has a Cobb–Douglas form.

Both the factor demand equations and the expressions for the user costs of capital follow from how firms minimize costs, given the production function (1). Let costs be equal to the sum of wage payments, costs of intermediates, and costs related to investments in R&D and fixed capital:

$$C_{jt} = W_{jt}H_{jt} + P_{Mjt}M_{jt} + q_t^{J^{RD}} J^{RD}_{jt} + q_j J_{jt} \tag{2}$$

Investment, J, in industry j in period t is determined by the capital accumulation equation, which states that gross investment equals net investment plus replacement for both R&D and fixed capital goods

$$\begin{aligned} J^{RD}_{jt} &= K^{RD}_{jt} - K^{RD}_{j,t-1} + \delta^{RD} K^{RD}_{j,t-1} \\ J_{jt} &= K_{jt} - K_{j,t-1} + \delta_j K_{j,t-1}, \end{aligned} \tag{3}$$

where depreciation is geometric, and depreciation rates for fixed capital (δ) vary across industries due to different capital asset compositions across industries, see Barth et al. (2016). The depreciation of R&D is assumed to be $\delta^{RD} = 0.15$ (i.e., 15 percent), measured in annual terms, in all industries, which is commonly used in the literature; see, e.g., Hall (2005).

Taxes are levied on wage payments and the costs of intermediates, but there are depreciation allowances for investments. Let total taxes net of depreciation allowance including a subsidy on R&D investment be given by

$$T_{jt} = \tau_t \left[W_{jt}H_{jt} + P_{Mjt}M_{jt} - z^{RD}_{jt} P_t^{J^{RD}} J^{RD}_{j,t-1} - z^J_{jt} P^J_{jt} J_{jt} \right] + \tau_c P_t^{J^{RD}} J^{RD}_{j,t-1}, \tag{4}$$

where τ is the corporation tax rate, τ_c is the subsidy rate on R&D investment, z^{RD}_{jt} represents the present value of the tax depreciation of 1 NOK invested in R&D capital, and z^J_{jt} represents the present value of 1 NOK invested in fixed capital investments. With geometrical tax depre-

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[2] An exhaustive list of symbols referred to in Sections 2-4 is given in Table 1.

[3] In Appendix B we provide a list of symbols used in Appendix A.

ciation we have

$$z_t^{RD} = tdr + \frac{1-tdr}{1+ir} tdr + \left(\frac{1-tdr}{1+ir}\right)^2 tdr + \ldots = \frac{tdr(1+ir)}{tdr+ir}, \tag{5}$$

where *tdr* is the tax depreciation rate for R&D investments, and *ir* represents the discount rate for shareholders. For R&D investments, all R&D expenses can be written off in the year the investment is made, and we have $z_t^{RD} = 1$. [4]

Firms minimize discounted after-tax costs

$$\min \sum_{t=0}^{\infty} \beta^t [C_t - T_t], \; s.t. \; (1), \; (2), \; (3), \tag{6}$$

where $\beta = \left(\frac{1}{1+ir}\right)$ is the discount factor. The solution to this minimization problem yields both factor demand equations and equations for the user-cost of capital. The factor demand equations are given by

$$\begin{aligned} K_{jt}^{RD} &= \alpha_{K^{RD}j}^{*}(X_{jt} \,/\, TFP_{jt})\left(P_{Kjt}/P_{K^{RD}t}\right)^{\alpha_{Kj}}\left(W_{jt}/P_{K^{RD}t}\right)^{\alpha_{Hj}}\left(P_{Mjt}/P_{K^{RD}t}\right)^{\alpha_{Mj}}, \\ K_{jt} &= \alpha_{Kj}^{*}(X_{jt} \,/\, TFP_{jt})\left(P_{K^{RD}t}/P_{Kjt}\right)^{\alpha_{K^{RD}j}}\left(W_{jt}/P_{Kjt}\right)^{\alpha_{Hj}}\left(P_{Mjt}/P_{Kjt}\right)^{\alpha_{Mj}}, \\ H_{jt} &= \alpha_{Hj}^{*}(X_{jt} \,/\, TFP_{jt})\left(P_{K^{RD}t}/W_{jt}\right)^{\alpha_{K^{RD}j}}\left(P_{Kjt}/W_{jt}\right)^{\alpha_{Kj}}\left(P_{Mjt}/W_{jt}\right)^{\alpha_{Mj}}, \\ M_{jt} &= \alpha_{Mj}^{*}(X_{jt} \,/\, TFP_{jt})\left(P_{K^{RD}t}/P_{Mjt}\right)^{\alpha_{K^{RD}j}}\left(P_{Kjt}/P_{Mjt}\right)^{\alpha_{Kj}}\left(W_{jt}/P_{Mjt}\right)^{\alpha_{Hj}}, \end{aligned} \tag{7}$$

where $\alpha_{K^{RD}j}$, α_{Kj}, α_{Hj}, and α_{Mj} are the output elasticities with respect to R&D capital, fixed capital, labor, and materials in industry *j*, respectively,[5] $\alpha_{K^{RD}j}^{*}$,α_{Kj}^{*},α_{Hj}^{*}, and α_{Mj}^{*} are constants that are non-linear functions of the output elasticities, $P_{K^{RD}t}$ and P_{Kjt} are, respectively, the user costs of R&D capital and fixed capital in industry *j* in period *t*.

The user cost of R&D capital follows the framework in Jorgenson and Griliches (1967) and Warda (2001) and is given by[6]

$$P_{K^{RD}t} = \frac{1-\tau-\tau_c}{1-\tau}(ir+\delta^{RD})q_t^{RD}, \tag{8}$$

where ***ir*** is the discount rate (and a function of the nominal interest rate and a risk premium), δ^{RD} is the actual depreciation rate, τ is the corporate income tax, and q^{RD} is the investment price.[7] The term $(1-\tau-\tau_c)/(1-\tau)$ is often referred to as the *B*-index. The *B*-index is defined as the present value of before tax income necessary to cover the initial cost of R&D investment and to pay corporate income tax. It measures how profitable it is to perform research activities. The *B*-index is equal to one when there is no tax credit ($\tau_c = 0$). It follows from Eq. (8) that a higher tax credit rate will lower the *B*-index and user cost of R&D. A lower user cost of capital generates higher R&D investment, see Eq. (7), which in turn impacts the overall level of productivity.

2.2. *Total factor productivity and R&D*

There seems to be a consensus in the literature that R&D is a key determinant of economic growth. For example, Coe et al. (2009) conclude that both domestic and foreign R&D capital have measurable impacts on productivity even after controlling for human capital. Using industry-level data for many OECD countries, but not including Norway, Bournakis (2012) found that international spillover is an important driver of labor productivity and that countries with stronger protection of intellectual property rights experience a larger increase in the effectiveness of spillovers.[8] Griffith et al. (2004) studied international R&D spillovers in a panel of 12 OECD countries, including Norway, and found that roughly half of the growth effects of higher R&D and skill intensity in TFP in Norwegian manufacturing are due to their proxy for technology transfer.

In line with Griffith et al. (2004), TFP by industry is assumed to depend on the R&D knowledge stock. This stock is modeled as a function of both domestic and international knowledge stock. In the literature following Coe and Helpman (1995) there is much discussion on the relative importance of domestic versus international spillovers from external R&D. In accordance with (Verspagen, 1997), the domestic knowledge spillovers,$K_{OTHj,t}^{RD}$, $j \in J^1$, are assumed to depend on a weighted sum of the R&D capital stocks in other domestic industries, see also Belderbos and Mohnen (2020) for an overview of how to measure technology spillovers.[9] They are included to capture domestic spillover effects affecting the industries considered. TFP by industry may also depend on the skill composition of the labor force by industry.

When constructing the variables $K_{OTH}^{RD}j, t$, ($j \varepsilon J^1$), we pay attention to the industries as both receivers and suppliers of intermediate inputs. Whereas the former activity is indicated by the upper-case letter *A*, the latter is indicated by the upper-case letter *B*. The spillover capital stocks attached to the two activities are given by, respectively,

$$K_{OTHA}^{RD}j, t = \sum_{i \in I^*} w_{ji} \times K_{it}^{RD}, \; where \; 0 \le w_{ji} \le 1 \; and \sum_{i \in I^*} w_{ji} = 1 \; \forall j \in J^1, \tag{9}$$

$$K_{OTHB}^{RD}j, t = \sum_{m \in I^{**}} ww_{jm} \times K_{mt}^{RD}, \; where \; 0 \le ww_{jm} \le 1 \; and \sum_{m \in I^{**}} ww_{jm} = 1 \; \forall j \in J^1, \tag{10}$$

with $w_{jj} = ww_{jj} = 0 \forall j \in J^1$.

The last set of restrictions means that own R&D capital stock, K_{jt}^{RD}, does not enter the capital stocks $K_{OTHA}^{RD}j, t$ and $K_{OTHB}^{RD}j, t$. The reason is that it enters the production function from which the TFP values have been derived. In Eqs. (9) and (10), *I** and *I*** denote, respectively, a set of all industries and a set of all industries except the public sector, see Table 2 below. Furthermore, recall that set J^1 contains all industries for which developments in TFP have been endogenized. The values of the time-invariant weights, see the w_{ji} and ww_{jm} symbols in Eqs. (9) and (10), are reported in Tables D1 and D2 in Appendix D.[10]

The final spillover capital stock, $K_{OTH}^{RD}j, t$ ($j \varepsilon J^1$), is given as a weighted mean of $K_{OTHA}^{RD}j, t$ and $K_{OTHB}^{RD}j, t$.

$$K_{OTH}^{RD}j, t = \rho_j K_{OTHA}^{RD}j, t + (1-\rho_j) K_{OTHB}^{RD}j, t, \; j \in J^1. \tag{11}$$

The share parameter, ρ_j, may vary from 0 to 1.

2.3. *Model specification and long-run properties*

We present below the econometric equations, where the left-hand side variables represent the relative change in TFP from one quarter to the next. The equations, in log-transformed variables, may be viewed as (non-linear) equilibrium-correction equations. They contain three main

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[4] For example, under the United States Generally Accepted Accounting Principles (GAAP), companies are obligated to expense R&D in the same fiscal year as the investment takes place. According to International Financial Reporting Standards (IFRS), research spending is treated as an expense each year, but development costs can be capitalized if the company can prove that the asset in development will become commercially viable.

[5] We assume constant return to scale, i.e. $\alpha_{K^{RD}j} + \alpha_{Kj} + \alpha_{Hj} + \alpha_{Mj} = 1, \forall j$.

[6] See Appendix C.

[7] The user price of R&D capital is assumed to be the same for all industries. The user price for fixed capital differs across industries due to different asset composition such that both the depreciation rate and the tax depreciation rate may be industry specific.

[8] In a related study, Bournakis and Mallick (2021) found that higher levels of corporate taxation impact adversely on TFP.

[9] Set J^1 consists of the industries for which we endogenize TFP.

[10] These weights are taken from input-output tables in the National Accounts.

Table 1
List of symbols used in the main part of the paper.

Symbol	Interpretation
X_{jt}	Gross production in industry *j* in period *t*
TFP_{jt}	Total factor productivity in industry *j* in period *t* (index)
M_{jt}	Intermediate input in industry *j* in period *t*
H_{jt}	Labor input in industry *j* in period *t*
K_{jt}	Stock of fixed capital in industry *j* at the end of period *t*
K_{jt}^{RD}	R&D capital stock in industry *j* at the end of period *t*
J_{jt}	Gross investment in fixed capital in industry *j* in period *t*
J_{jt}^{RD}	Gross investment in R&D capital in industry *j* in period *t*
C_{jt}	Total costs of industry *j* in period *t*
P_{Mjt}	Price of intermediate input in industry *j* in period *t* (index)
W_{jt}	Hourly wage in industry *j* in period *t*
$q_t^{J^{RD}}$	Purchasing price for R&D capital in period *t*
q_{jt}	Purchasing price for fixed capital in industry *j* in period *t*
W_{jt}	Hourly wage in industry *j* in period *t*
P_{Kjt}	User cost of fixed capital in industry *j* in period *t*
P_{Kjt}^{RD}	User cost of R&D capital in industry *j* in period *t*
τ_t	Corporation tax rate in period *t*
τ_c	Subsidy rate on R&D investment (through SkatteFUNN)
tdr	Tax depreciation rate for R&D investments
Q_t	Sum of value added in all eight modeled industries
P_{Qt}	Implicit price deflator of Q_t
w_{Hjt}	Wage expenses as a share of total costs in industry *j* in period *t*
w_{Mjt}	Intermediate input expenses as a share of total costs in industry *j* in period *t*
w_{KKjt}	Capital expenses (covering both fixed and intangible assets) as a share of total costs in industry *j* in period *t*
J_{jt}	Gross fixed investment in industry j in period *t*
$K_{OTHA}^{RD}j,t$	Component of spillover aggregate (stemming from the industry as a receiver of products) of industry *j* in period *t*, $j = 1, \ldots, 8$
$K_{OTHB}^{RD}j,t$	Component of spillover aggregate (stemming from the industry as a supplier of products) of industry *j* in period *t*, $j = 1, \ldots, 8$
$K_{OTH}^{RD}j,t$	Spillover aggregate of industry *j* in period *t*, $j = 1, \ldots, 8$
SK_{jt}	Share of skilled workers in industry j in period t, j = 1, …,8
ir	Discount rate for shareholders
δ^{RD}	Depreciation rate for R&D capital
δ_j	Depreciation rate for fixed capital in industry *j*
w_{ji}	Weight of industry *i* in the construction of $K_{OTHA}^{RD}j,t$
ww_{ji}	Weight of industry *i* in the construction of $K_{OTHB}^{RD}j,t$
ω_{ji}	Linear combination of w_{ji} and ww_{ji}
α_{Mj}^*	Coefficient of the conditional demand function for intermediate input in industry *j*
α_{Hj}^*	Coefficient of the conditional demand function for labor in industry *j*
α_{Kj}^*	Coefficient of the conditional demand function for fixed capital in industry *j*
$\alpha_{K_j^{RD}}^*$	Coefficient of the conditional demand function for R&D capital in industry *j*
α_{Mj}	Output elasticity of material input in industry *j*
α_{Hj}	Output elasticity of labor in industry *j*
α_K	Output elasticity of fixed capital in industry *j*
α_{Kj}^{RD}	Output elasticity of R&D capital in industry j
ρ_j	Share parameter related to spillover aggregate in industry j (j = 1, …,8). It is set at 0.5 for all eight industries.
γ_j	Adjustment parameter in equation for relative change in TFP for industry *j*, $j = 1, \ldots, 8$
λ_j	Short-run parameter in equation for relative change in TFP for industry *j*,
η_j	Slope parameter related to domestic spillover effect for industry *j*, $j = 1, \ldots, 8$
φ_j	Slope parameter related to foreign spillover effects for industry *j*, $j = 1, \ldots, 8$
κ_j	Slope parameter related to skill share for industry *j*, $j = 1, \ldots, 8$
$\xi_{j,1}$	Long-run parameter related to foreign TFP in the TFP equation for industry *j*, $j = 1, \ldots, 8$
$\xi_{j,2}$	Long-run parameter related to domestic spillover aggregates for industry *j*, $j = 1, \ldots, 8$
$\xi_{j,3}$	Long-run parameter related to skill-share variables for industry *j*, $j = 1, \ldots, 8$
$\varepsilon_{j,t}$	Error term in the econometric relationship of TFP for industry *j* in period *t*, $j = 1, \ldots, 8$
$\underline{\varepsilon}_t$	Vector with errors from the endogenized TFP relationship in period *t*
Ω	The (time-invariant) covariance matrix of $\underline{\varepsilon}_t$
J^1	Set of industries for which TFP is endogenized
I^*	Set of all industries
I^{**}	Set of all industries less government sector

Table 2
Industries in the model and some additional information, 2016

Current number	Industry	Employment share	Value added share	R&D capital stock[a]	R&D spillover stock[a]
1	Agriculture, fishing and forestry	2.5	2.4	2377	25,579
2	Manufacturing of consumer goods	4.1	3.6	16,219	
3	Energy-intensive manufacturing	0.7	0.8	5710	
4	Manufacturing of machinery	3.8	3.1	27,472	39,332
5	Power generation	0.5	2.2	6247	48,568
6	Wholesale and retail trade	13.6	8.4	19,676	35,342
7	Other private services	32.1	27.6	105,677	13,643
8	Real estate activities	0.9	3.3	1514	45,812
9	Construction	8.2	6.6		
10	International shipping services	1.3	1.0		
11	Oil and gas extraction	1.0	13.7		
12	Services related to oil and gas extraction	0.9	1.3		
13	Government sector	30.3	21.3		
14	Housing services	0	4.7		

[a] Capital stock at the end of the year. Millions of NOK.

explanatory variables that may influence the relative change in TFP: the spillover capital stock from other domestic industries, $K_{OTHj,t-1}^{RD}$, the index for the development of *TFP* in the US, $TFP_{US,t-1}$ and the share of skilled workers in the industry, $SK_{j,t-1}$. The TFP for the US is used as a proxy for international TFP. Rabanal et al. (2011) show that the TFP level in the US cointegrate with the TFP level for the rest of the world, implying that they follow the same stochastic trend. It is interacted with the knowledge capital stock of own industry, i.e., $K_{j,t-1}^{RD}$, to capture the absorption effect, i.e., the more an industry spends on R&D, the more it will be able to absorb international knowledge. Note that all four variables mentioned above are lagged one quarter and that the two capital stocks are measured at the end of the quarter. The lagged relative change in the TFP is also included in the model specification. Before ending up with the specification given by Eq. (12) we also considered other specifications, e.g., specifications involving longer lags and interaction effects between $K_{OTHj,t-1}^{RD}$ and $SK_{j,t-1}$, which did not produce results that were easy to interpret.

$$\begin{aligned}\Delta\ln\left(TFP_{j,t}\right) = \quad & \text{determinstic terms} + \gamma_j \Delta\ln\left(TFP_{j,t-1}\right) \\ & +\lambda_j \ln\left(TFP_{j,t-1}\right) + \eta_j \ln\left(K_{OTHj,t-1}^{RD}\right) \\ & +\varphi_j \ln\left(K_{j,t-1}^{RD}\right)\ln\left(TFP_{US,t-1}\right) + \kappa_j SK_{j,t-1} + \varepsilon_{j,t},\end{aligned} \tag{12}$$

where ε_{jt} denotes an error term. We consider 8 industries and assume that $\underline{\varepsilon}_t = [\varepsilon_{1,t}, \quad \varepsilon_{2,t}, \ldots, \varepsilon_{8,t}]' \; t = 1, \ldots, T$, are $NIID\left(\underline{0}, \; \Omega\right)$, where $\underline{0}$ is an 8×1 vector of zeros and Ω is a full positive-definite covariance matrix. The right-hand variables are assumed to be either strictly exogenous or predetermined.

In the partial model given by Eq. (12), the long-run relationship, neglecting deterministic terms, is given by

$$\ln\left(TFP_{j,t}\right) = -\frac{\varphi_j}{\lambda_j}\ln\left(K_{j,t}^{RD}\right) \times \ln(TFP_{US,t}) - \frac{\eta_j}{\lambda_j}\ln\left(K_{OTH}^{RD}j,t\right) - \frac{\kappa_j}{\lambda_j}SK_{j,t},\ j \in J^1. \tag{13}$$

Eq. (13) is obtained by setting the differenced variables on both the left- and the right-hand sides of the equation equal to zero and dropping deterministic and error terms.

In the long run, the (log of) the TFP index depends on three terms: $\ln(K_{j,t}^{RD}) \times \ln(TFP_{US,t})$, $\ln(K_{OTH}^{RD}j,t)$, and $SK_{j,t-1}$. It is convenient to define $\xi_{j,1} = -\varphi_j/\lambda_j$, $\xi_{j,2} = -\eta_j/\lambda_j$, and $\xi_{j,3} = -\kappa_j/\lambda_j$, $j \in J^1$ for later use. From Eq. (13), we can derive various long-run elasticities of interest. The long-run elasticities with respect to TFP in the US and the spillover aggregate are given by, respectively,

$$\frac{\partial\ln\left(TFP_{j,t}\right)}{\partial\ln\left(TFP_{US,t}\right)} = \xi_{j,1}\ \ln\left(K_{j,t}^{RD}\right), \tag{14}$$

$$\frac{\partial\ln\left(TFP_{j,t}\right)}{\partial\ln\left(K_{OTH}^{RD}j,t\right)} = \xi_{j,2},\ j \in J^1 \tag{15}$$

whereas

$$\frac{\partial\ln\left(TFP_{j,t}\right)}{\partial SK_{j,t}} = \xi_{j,3},\ j \in J^1. \tag{16}$$

is a semi-elasticity with respect to the skill variable, $SK_{j,t}$. It is also of interest to investigate the long-run elasticities of the TFP level in a given industry with respect to the R&D capital stock in another industry. They are given by

$$\frac{\partial\ln\left(TFP_{j,t}\right)}{\partial\ln\left(K_{i,t}^{RD}\right)} = \omega_{ji}\left(\frac{K_{i,t}^{RD}}{K_{OTH}^{RD}j,t}\right)\xi_{j,2};\ j \in J^1;\ i \in I^*, \tag{17}$$

where $\omega_{ji} = \rho w_{ji} + (1-\rho)ww_{ji}\ j \in J^1; i \in I^*$.

2.4. *Aggregate productivity growth*

TFP by industry is defined through a gross production function; see Eq. (1). However, the aggregated TFP is defined through the valued added production function, which does not include intermediate inputs since intra economy flows of domestically produced output are netted out. Therefore, the link between aggregated TFP and TFP by industry can be formulated using the Domar index, see also Appendix E. This link was explored by Domar (1961) and developed further by Hulten (1978); see also Balk (2009).

$$\Delta\ln TFP_t = \sum_{j \in J^1}\left(P_{jt}X_{jt}/P_{Qt}Q_t\right)\Delta\ln TFP_{jt}, \tag{18}$$

where the weights are the value of gross output in industry j divided by the sum of value added across all industries. Note that the sum of the weights exceeds unity, which implies that productivity growth at aggregate level amounts to more than the weighted average of industry-level productivity growth. This reflects the fact that productivity gains in the production of intermediate inputs lead to reduced input prices in downstream industries, and thus a higher level of aggregate productivity.

2.5. *How R&D tax credits affect economic growth*

The analytical results above illustrate how R&D tax credit impacts economic growth through factor demand changes. An increase in tax credits lowers the user cost of R&D, see Eq. (8). A lower R&D user cost leads to higher R&D investment and higher R&D capital, see Eq. (7). This, in turn, will lead to increased productivity at the industry level both through higher own R&D investment in the industry, but also through a higher spillover pool of knowledge from other domestic industries; see Eq. (12). At the aggregate level, these effects are multiplied further, since productivity gains in the production of intermediate inputs lead to reduced input prices in downstream industries, and thus a higher level of aggregate productivity through the Domar weighting scheme; see Eq. (18).

Table 3
Summary statistics of 4-quarter growth in TFP indices of modeled industries, in percent.[a]

Industry	Mean	Std. dev.	Minimum	Maximum
Agriculture, fishing and forestry (1)	3.10	4.45	−9.81	16.45
Manufacturing of consumer goods (2)	0.36	1.11	−4.09	3.71
Energy-intensive manufacturing (3)	0.52	2.47	−7.68	7.47
Manufacturing of machinery (4)	0.62	1.49	−5.36	4.75
Power generation (5)	1.43	8.76	−20.34	29.39
Wholesale and retail trade (6)	1.94	2.25	−4.75	10.67
Other private services (7)	0.68	1.54	−4.24	4.59
Real estate services (8)	0.21	5.07	−12.33	14.28
US	0.74	0.92	−2.07	3.12

[a] Time period 1982q1-2017q4. The numbers in parentheses in the text column are current industry numbers; see Table 2.

3. Data

Data on R&D, capital, employment, gross production, etc., have been taken from Statistics Norway's National Accounts.[11] The international spillover variable, measured using the productivity index TFP for the US, has been taken from the Conference Board.[12] The domestic gross production productivity index by industry, TFP_t, is constructed using the following formula

$$\Delta\ln TFP_{jt} = \Delta\ln X_{jt} - w_{KKjt}\Delta\ln\left(K_{jt} + K_{jt}^{RD}\right) - w_{Hjt}\Delta\ln H_{jt} - w_{Mjt}\Delta\ln M_{jt}, \tag{19}$$

where $K_{jt} + K_{jt}^{RD}$ is the aggregate capital level, covering both fixed and intangible capital; see alse Appendix E. Furthermore, w_{KKjt}, w_{Hjt} and w_{Mjt} are the weights for aggregate capital, labor, and materials in industry j in period t. Three aspects of the weights merit attention: first, the weights for labor and materials are constructed as the costs of labor and materials, respectively, relative to the value of gross output. The weight for aggregate capital level is defined residually as: $ww_{KKjt} = 1 - w_{Hjt} - w_{Mjt}$. Second, since we construct these series using quarterly data we have chosen a weighting scheme based on nominal shares in gross production from the average of the four most recent quarters. This is consistent with the weighting scheme used in the National Accounts, but differs from the weighting scheme that follows from a superlative index such as the Törnqvist index; see Diewert (1976).[13] Third, labor costs have been calculated assuming that the average wage level of the self-employed is the same as that of wage earners in the same industry. Note that the effect of the industry's own R&D capital stock is included when calculating TFP by industry. So any further effects of R&D capital stocks on TFP by industry are evidence of spillovers from R&D. We will sometimes refer to an aggregate industry called "Mainland business sector". This aggregate comprises the industries 1 to 9 and 12 in Table 2.

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[11] See Statistics Norway: https://www.ssb.no/en/nasjonalregnskap-og-konjunkturer/statistikker/knr.

[12] See the Conference Board: https://www.conference-board.org/data/economydatabase/index.cfm?id=27762.

[13] In some quarters (for example for the primary industries in the mid-1980s), the nominal value of intermediates and labor costs exceeded the nominal value of gross production. In these cases, the capital weight is set to zero and the weights of labor and intermediates are adjusted down proportionally so that they add up to unity.

Table 4
Summary statistics of 4-quarter growth in R&D capital stocks in industries with endogenized TFP, in percent.[a].

Industry	Mean	Std. dev.	Minimum	Maximum
Agriculture, fishing and forestry (1)	12.664	11.713	−13.744	43.231
Manufacturing of consumer goods (2)	3.596	4.847	−7.134	17.663
Energy-intensive manufacturing (3)	2.467	5.563	−7.637	18.710
Manufacturing of machinery (4)	2.986	4.965	−4.708	17.991
Power generation (5)	8.198	12.707	−21.074	67.268
Wholesale and retail trade (6)	9.298	7.594	−7.047	31.763
Other private services (7)	7.077	6.922	−0.255	33.657
Real estate services (8)	11.968	15.856	−32.857	51.222

[a] Time period 1982q1-2017q4. The level series are at constant 2016 prices. Million of 2016 NOK. The numbers in parentheses in the text column are current industry numbers; see Table 2.

Table 5
Summary statistics of 4-quarter growth in R&D spillover aggregates of relevance for econometric TFP relations, in percent.[a].

Industry	Mean	Std. dev.	Minimum	Maximum
Agriculture, fishing and forestry (1)	4.958	4.787	−3.711	20.688
Manufacturing of machinery (4)	6.789	5.974	0.296	29.425
Power generation (5)	6.531	6.071	0.051	29.260
Wholesale and retail trade (6)	5.909	5.622	−0.858	25.876
Other private services (7)	4.234	3.626	−3.243	15.459
Real estate services (8)	6.537	5.466	0.292	26.739

[a] Time period 1982q1-2017q4. At constant 2016 prices. Millions of 2016 NOK. The numbers in parentheses in the text column are current industry numbers; see Table 2.

Table 6
Maximum likelihood estimates for the system of equilibrium-correction equations.[a].

Parameter	Related variable(s)	Estimate	*t*-value
γ_2	$\Delta\ \ln(TFP_{2,t-1})$	−0.2395	−3.7024
γ_4	$\Delta\ \ln(TFP_{4,t-1})$	−0.3276	−5.2421
γ_6	$\Delta\ \ln(TFP_{6,t-1})$	−0.3449	−11.4826
γ_8	$\Delta\ \ln(TFP_{8,t-1})$	−0.3911	−6.8298
λ	$\ln(TFP_{j,t-1}); j = 1, \ldots,8$	−0.0728[b]	−6.6664
η	$\ln(K^{RD}_{OTH}j, t-1); j = 1,4,5,6,7$	0.0041	2.2064
η_8	$\ln(K^{RD}_{OTH}8, t-1)$	0.0137	2.3820
φ	$\ln(TFP_{US,t-1})^{*}\ln(K^{RD}_{j,t-1})\ ; j = 1, \ldots,8$	0.0038	3.7537
κ_5	$SK_{5,t-1}$	0.1254	2.1607
κ_6	$SK_{6,t-1}$	0.3957	5.8536

[a] The digits in the subscripts indicate industry numbers; see Table 1. The model also contains a constant term and seasonal variables, but the estimates of intercepts and seasonal effects are not included in this table.

[b] A priori restriction.

Table 7
Estimates of derived long-run parameters.

Derived long-run parameter	Interpretation	Equation(s) involved	Estimate	*t*-value[a]
$\xi_{j,1}; j = 1, \ldots, 8$	Foreign spillover effect	1–8	0.0518	4.4329
$\xi_{j,2}; j = 1, 4, 5, 6, 7$	Domestic spillover effect	1,4,5,6,7	0.0563	2.4396
$\xi_{8,2}$	Domestic spillover effect	8	0.1886	2.5462

[a] Calculated by the delta method.

Table 8
The long-run elasticity of the TFP level in industry *j* with respect to the US TFP level.[a].

Industry	Estimate	Industry	Estimate
1	0.3159	4	0.5161
2	0.4810	5	0.3790
3	0.4415	6	0.4273
7	0.5498	8	0.2929

[a] The formula applied is $\ln(K^{RD}_j)\xi_{j,1}$ [Evaluation is performed at the sample mean of $\ln(K^{RD}_j)$]. In all eight cases, the *t*-value is 4.3293.

Some summary statistics related to the main variables are provided in Tables 3–5 below.

Table 3 concerns 4-quarter percentage growth in TFP variables. As expected, all the mean growth rates are positive, but the growth rates of several of the TFP variables vary considerably over the sample period. The two highest mean growth rates are found for Agriculture, fishing and forestry and Wholesale and retail trade. In contrast, the two lowest are found for Real estate services and Manufacturing of consumer goods. The mean percentage growth in TFP for the US is somewhat higher than for the two Norwegian industries with the lowest mean growth. The underlying time series varies has lower standard deviation than the Norwegian series across the sample period.

Table 4 provides summary statistics for the percentage stocks of R&D capital in the industries with modeled TFP. The mean growth rates differ markedly across industries. The highest mean growth rates are found for Agriculture, fishing and forestry, and Real estate services, and the lowest for Energy-intensive manufacturing and Manufacturing of machinery. All eight growth rates vary substantially. The highest volatilities are for Real estate services and Power generation. All the eight industries have experienced a decrease in R&D capital over a four quarter period (as the minimum growth rates are negative in the table), and all the eight maximum growth rates exceed 17 percent. Since the rate of depreciation is high, in some years depreciation exceeds gross investment in R&D capital.

In Table 5 we report summary statistics of spillover aggregates for the six industries in which the spillover aggregate is used as an explanatory variable. The mean growth rates are quite similar across the six industries, varying from 4.2 percent for Other private services to 6.8 percent for Manufacturing of machinery. The standard deviations are also fairly similar across the industries. For three industries, growth rates are positive throughout the sample, as seen from the minimum value column. The maximum growth rates vary from about 15 to 29.5. Thus, there is substantial variation, also for the growth rates of spillover aggregates, in each industry during the sample period.

For two of the industries for which TFP is endogenized, Power generation and Wholesale and retail trade, we utilize a skill-share variable as an explanatory variable. It is defined as the number of employed individuals with at least 13 years of education relative to all employed individuals in the industry. Owing to a persistent increase in educational attainment during the sample period, both series show an upward trend. Growth in Wholesale and retail trade has been somewhat higher than in Power generation. The mean skill shares during the sample period are 0.268 and 0.119, respectively, in the two industries.

4. Estimated TFP relations and derived results

The unknown first and second order parameters of the set of regression equations given by Eq. (12) have been estimated jointly by iterative SUR estimation, which coincides with maximum likelihood estimation using data from the period 1981q4-2017q4.[14] The share parameter ρ_j has

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[14] All estimations are done using TSP 5.1, see Hall and Cummins (2009).

Table 9
The long-run elasticity of the TFP level in industry *j* with respect to the R&D capital stock in industry *i*[a].

j	i												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0[b]	0.03018	0.00093	0.00162	0.00040	0.00079	0.02124	0.00000	0.00013	0.00000	0.00099	0.00000	0.00000
4	0.00004	0.00131	0.00187	0[b]	0.00034	0.00244	0.04742	0.00005	0.00030	0.00001	0.00038	0.00026	0.00185
5	0.00009	0.00195	0.00152	0.00327	0[b]	0.00085	0.04681	0.00011	0.00014	0.00000	0.00059	0.00006	0.00088
6	0.00011	0.00430	0.00137	0.01048	0.00034	0[b]	0.03895	0.00015	0.00023	0.00001	0.00019	0.00014	0.00000
7	0.00016	0.01021	0.00175	0.02205	0.00173	0.00435	0[b]	0.00037	0.00042	0.00011	0.00426	0.00028	0.01059
8	0.00000	0.00487	0.00166	0.01148	0.00232	0.01063	0.14440	0[b]	0.00108	0.00000	0.00087	0.00011	0.01122

[a] The formula applied is $\omega_{ji}(K_i^{RD}/KOTH_j^{RD})\xi_{j2}$. (Evaluation is performed at the sample mean of the capital ratio).

[b] A priori restriction.

been set at 0.5 for all eight industries with endogenized TFP.[15] In order to eliminate insignificant parameter estimates and increase estimation efficiency, we have imposed the following restrictions in Eq. (12): $\gamma_j = 0$ ($j = 1,3,5,7$); $\lambda_j = \lambda$ ($j = 1, \ldots, 8$); $\eta_2 = \eta_3 = 0$; $\eta_j = \eta$ ($j = 2,4,5,6,7$); $\varphi_j = \varphi$ ($j = 1, \ldots, 8$); $\kappa_j = 0$ ($j = 1,2,3,4,7,8$). Table 3 contains estimates of first-order parameters. Except for some of the deterministic terms, the parameter estimates are significant. The parameter estimates of the key explanatory variables have the correct sign. Table F1 (in Appendix F) contains some diagnostics, and Table F2 reports the estimated covariance matrix of the error vector. The DW statistics for residual autocorrelation are in the range of 1.9–2.6, with the highest value found for industry 7.[16] For industry 8 there are some sign of heteroskedasticity in the residuals.

From the results reported in Table 6, we can derive the elasticities of the long-run parameters. They are reported in Tables 7 and 8. As seen in Table 7, there is a common estimated long-run effect on the log of the TFP level of the product between the log of the US TFP level and the log of own stock of R&D capital for all eight industries. The estimate is about 0.05. Table 8 contains estimates of the elasticity of the industry-specific TFP level with respect to the US TFP level. Note that this is not an estimate of a parameter, since it also depends on the level of own industry R&D capital stock. The largest estimated effects are found for industry 7, followed by industries 4 and 2. They are 0.55, 0.52, and 0.48, respectively. For the other industries, the estimates are about in the range 0.29–0.44.

For industries 1, 4, 5, 6 and 7, there is a significant estimated elasticity with respect to the spillover capital aggregate of R&D capital in other Norwegian industries of 0.056. The long-run spillover effects from the single industries to industries 1, 4, 5, 6, and 7 may also be considered; see Table 9. Industry 2 contributes most to the spillovers to industry 1, whereas industry 7 is most important to industries 4, 5, 6 and 8. For industry 7, industry 4 is the most important.

The *SK* variable is included in industries 5 and 6, whereas it proved to enter insignificantly in the other six industries. Our significant estimates (at the 5 percent significance level) of the long-run parameters $\xi_{5,3}$ and $\xi_{6,3}$ are quite high and indicate that an increase in skill shares amounting to one percentage point yields increases in the TFP level equal to 1.7 and 5.4 percent, respectively.

The estimate of the common adjustment parameter, λ, is -0.073. In four of the industries, i.e., industries 2, 4, 6, and 8, there is a significant and negative estimate of the parameter of the lagged left-hand variable, $\Delta\ln\left(TFP_{j,t-1}\right)$ However, when transforming the equations back to level form, one might infer that both the first and the second lag of the response variable, i.e., $\ln\left(TFP_{j,t-1}\right)$ and $\ln\left(TFP_{j,t-2}\right)$, enter with positive values.

Based on the estimated model, we can decompose the growth of TFP at aggregate level for Norway during a period (1982–2018) where historical data are available. We aggregate TFP by industry using the Domar index, see Eq. (18), Fig. 1 compares historical TFP data for mainland business sectors with the simulated results (using dynamic simulation).

First, we note that the estimated model tracks the actual TFP level quite well within the sample. Our level of aggregation corresponds to the mainland business sector in the Norwegian economy excluding Construction and Services related to oil and gas extraction. The average annual TFP growth rate during the simulation period is 1.8 percent using the Domar index and 0.7 percent using gross output volumes as weights. This implies that the ratio between gross output and value added for our aggregate is roughly 2.5.

In the following we decompose how the various explanatory TFP factors by industry have contributed to aggregate TFP growth by conducting several counterfactual simulations.[17] First, we construct a baseline simulation using only the estimated TFP equations; all explanatory variables in these equations are shown in Table 6. All explanatory variables in the TFP equations are kept constant at their initial 1981 values. The value of the Domar index is then almost constant from 1982 to 2018. We then let TFP in the US follow its historical development instead of remaining constant as in the baseline simulation, and compare the Domar index in this simulation with the baseline.

Table 10 shows that this partial effect of higher TFP in the US resulted in 35 percent higher TFP in 2018. Next, we let the Norwegian R&D

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[15] These shares could in principle vary both across industries and time. In an attempt to estimate time-invariant shares, it proved difficult to obtain significant and interpretable estimates. Acharaya (2015), in a rather comprehensive analysis for the OECD countries, involving 28 industries, emphasized the asymmetric flows of technology across industries, but he does not distinguish between input and output activities by industry.

[16] The DW statistic, which is the only one TSP reports for residual autocorrelation, is not very informative in our setting with lagged endogenous variables and cross-equation restrictions.

[17] To be explicit, consider the function y = f(x,z). The direct contribution of the change in x (dx) to the change in y (dy) is given by f(x + dx,z), and the direct contribution of the change in z (dz) to the change in y is given by f(x, z + dz). The change in y (dy) that does not stem from the direct changes in x or z is labelled combined effect, i.e. dy-f(x + dx,z)-f(x, z + dz); see also Benedictow and Boug (2017, Appendix 2).

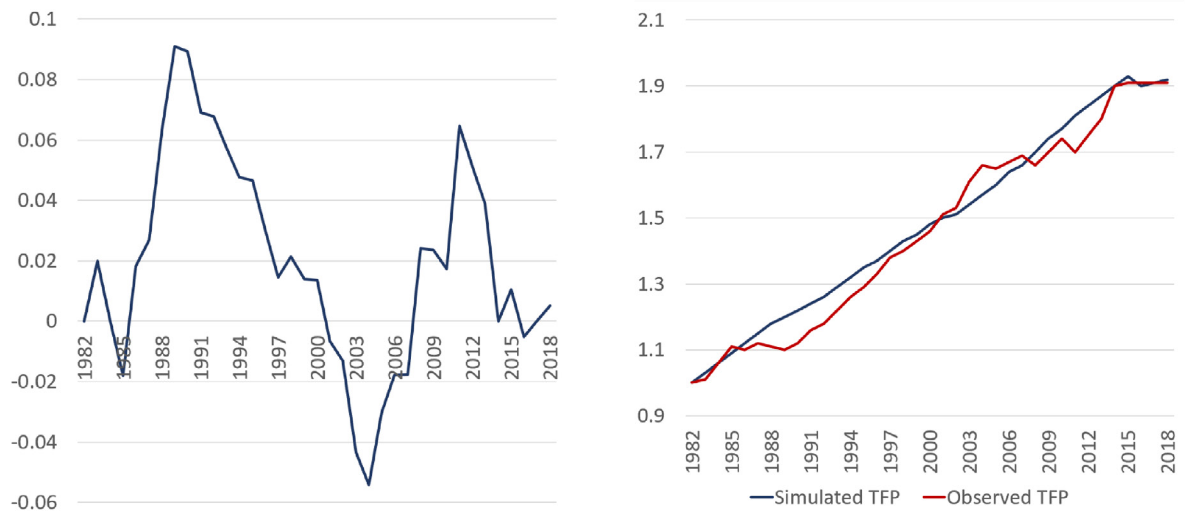


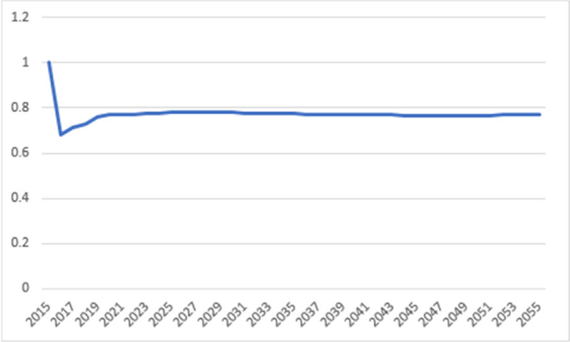
Fig. 1. Estimated errors (left-hand panel) and simulated and actual TFP (right-hand panel). 1982–2018.

Table 10
Decomposition of increase in total TFP 1982–2018.

Source	Percent
Increase due to domestic R&D capital	16
Increase due to domestic skills ratio	19
Increase due to higher TFP_{US}	35
Combined effect of TFP_{US} and R&D capital	8
Combined effect of TFP_{US} and skills ratio	9
Combined effect of R&D capital and skills ratio	5
Total	92

capital stocks follow their historical development and estimate their effects on the Domar index by comparing it with the baseline. Finally, we do the same with the skill ratios (*SK*) to estimate the effect on aggregate TFP of their historical increase. The results of these two simulations compared to the baseline are shown in the first two lines of Table 10. Because the model is non-linear, see Eq. (12), there are interaction effects of these partial changes in the explanatory variables that we need to include as well. We therefore end up with three partial effects and three interaction effects. Their contribution to the overall growth in TFP, measured by the Domar index, is shown in Table 10. The total increase in TFP, according to the Domar index, is 91 percent over the whole sample period, which implies that the factors specified contributed to 1.8 percent annual growth in aggregate TFP in Norway in the period 1982–2018.

We can compare some of these results with those in table 3 in Griffith et al. (2004), who conducted a similar analysis. They found that roughly half of the growth effects of higher R&D and skill intensity in TFP in Norwegian manufacturing is due to their proxy for domestic technology transfer. Our results for the Norwegian business sector as a whole are slightly smaller. The total growth effect of higher skills is 19 + 9 percentage points, so the technology transfer effect is roughly one third. A similar effect applies for R&D capital (16 + 8 percentage points), and technology transfers amount to one third of the total effect in this case too. There is an additional interaction effect between the two domestic sources of TFP growth: R&D capital and skill intensity, but this is small. The partial domestic effect on TFP growth amounts to $(16 + 19 + 5)/92 = 0.435$, while the partial international transfer effect is $35/92 = 0.38$ (or 38 percent). The remaining interaction effects between domestic sources and international transfers are $17/92 = 0.185$ of total TFP growth. These results are also in line with Coe et al. (2009), who concluded that both domestic and foreign R&D capital have measurable impacts on TFP even after controlling for human capital. The importance of skills for innovation is also highlighted by Bye and Fæhn (2012) in a CGE analysis for Norway.



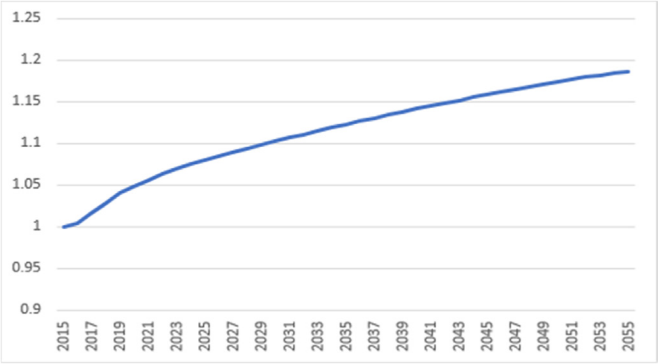
Note: Simulated change in user cost of R&D due to a 10 percentage point increase in the tax deductibility rate (*tdr*)

Fig. 2. The user cost of R&D capital in the policy scenario compared to the baseline scenario.

5. Policy simulations

Norway introduced a tax credit system (SkatteFUNN) for R&D in 2002 to stimulate R&D investment in the business sector, cf. Cappelen et al. (2010). The introduction of this tax credit system led to a reduction in the user cost of R&D capital, as can be seen from Eq. (8). In the case of Norway in 2019, $\tau = 0.22$ while $\tau_c = 0.18$ for a large firm (0.20 for SMEs) so $B_{2019} = 0.77$ (0.74 for SMEs), implying that this tax credit system reduced the user cost of R&D capital by 23 percent for large firms (26 percent for SMEs). Note however, that this effect on user cost is only relevant for firms with R&D investment that is lower than the upper limit or cap in the system. Although most firms do in fact belong to this group, there are large firms with large R&D expenditures that spend more than the cap every year. For these firms, the user cost is unchanged. Our model simulations are based on a reduction in the user cost of R&D capital of 23 percent; see Fig. 2.

The next question we need to address is the financing of tax credits. An increase in tax deductions for R&D increases profits that are taxed using the corporate tax rate of 0.22. But tax deductions are larger, so corporate income tax revenue is reduced. After a few years, the revenue loss is roughly NOK 2 billion or EUR 200 million according to our model simulations. To finance this revenue loss, we reduce government transfers by a similar amount. We do not balance the total government budget in each year in the same way in both simulations. Instead, we focus on the long-run balance and government net assets as a share of nominal GDP. In this way, the two policies will have the same long-run fiscal balance. This is in line with the Norwegian fiscal policy rule. Our choice to use transfers



Note: Model simulations of a 23 percent negative shift in R&D user cost compared to baseline.

Fig. 3. The effect on R&D capital stock in mainland (non-oil) industries.

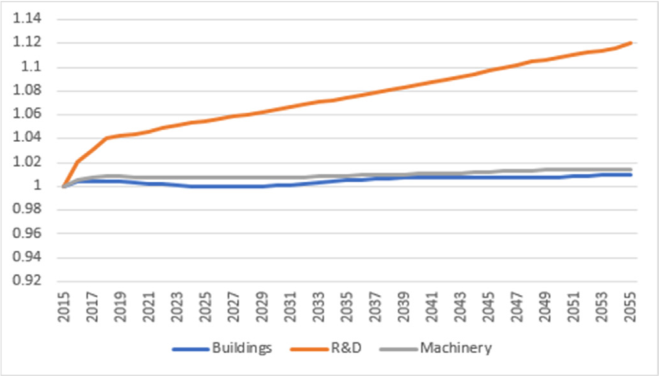
to households is motivated by utilizing a variable with limited effect on incentives such as income tax rates.

The permanent reduction in the user cost of R&D capital will gradually increase the R&D capital stock in the private sector mainland economy.[18] This is shown in Fig. 3. Because of the slow response of capital stock to changes in user cost, the increase in capital stock will be very gradual. There will also be some increase in capital stock and more investment as a second-round effect of the initial reduction in user cost. We return to this feature below. We study policy shift over a 40-year horizon to illustrate the slow response of the spillover effects and the ripple effects of these spillovers for the rest of the economy.

Fig. 4 shows the effects on gross investment for three main asset types. The effects on R&D investment are substantial, while the effects on the other two major categories are quite moderate. Consequently, the aggregate capital stocks of buildings and machinery will not change much either. Besides being affected by changes in the user cost of R&D capital, capital stocks by industry are affected by gross output and TFP. Output increases following the decline in user costs lead to an increase in demand for capital of all categories in line with Eq. (7), while the increase in TFP will lower demand for capital, ceteris paribus. The net effect of these two elements is what we see in Fig. 4.

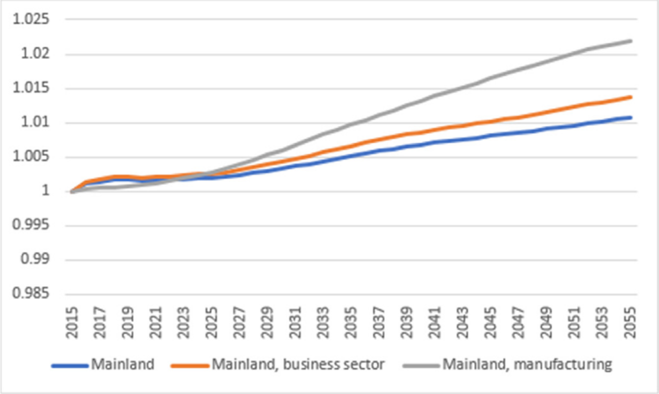
The effects on value added for two aggregates are shown in Fig. 5. For Mainland GDP (total GDP excl. petroleum extraction and international shipping services) we notice that the cut in the user cost affects output with a long lag. One reason is the balanced budget policy assumption, whereby cutting transfers to households means that consumption is reduced. The other reason for the sluggish response is that it takes time to increase the R&D capital stock enough to generate productivity and spillover effects. This explains why there is almost no aggregate effect on GDP in the first decade following the cut in the user cost of capital. The effect on the mainland business sector is somewhat larger, since by assumption there are no changes in government employment or investment. After the first decade, there are steadily larger aggregate output effects. Notice also that these effects do not move towards a new equilibrium level but increase during the entire simulation period. Thus, the growth rate of the economy is affected by the stimulus to R&D in line with some models of endogenous growth.

The main reason for the effect on GDP growth is the change in TFP in various industries. This is shown in Figs. 6 and 7, which display changes in TFP for three manufacturing industries and various other private sector industries. For most industries, TFP increases by around one percent. This is only due to the spillover effect of higher R&D capital in Norway. From the presentation of the model in Section 2, we notice that R&D capital by industry is included in the total capital stock by industry with standard "neoclassical" effects. In addition, R&D affects industry TFP through spillovers from R&D capital in other industries. Looking at the macroeconomic effects in Table 11, we see that total employment declines while the total capital stock increases due to this policy shift. The increase in the capital stock is a result of the increase in gross investment, as shown in Fig. 4. According to Fig. 6, the industry Production of machinery and transport equipment enjoys most spillover within the manufacturing sector. The reason why the two other manufacturing industries (Manufactoring of consumer goods and Energy-intensive manufacturing (metals, fertilizers, and paper and pulp)) are not much



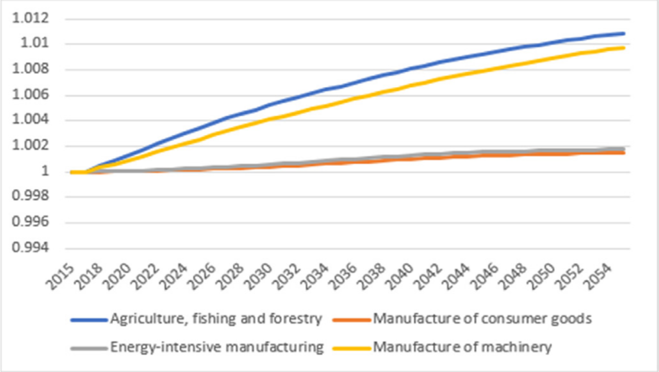
Note: Model simulation of a negative shift in the user cost of R&D.

Fig. 4. Effects on gross investment. Buildings, R&D and machinery.



Note: Model simulation of a negative shift in the user cost of R&D.

Fig. 5. Effects on mainland GDP and manufacturing.



Note: Model simulation of a negative shift in the user cost of R&D.

Fig. 6. Effects on total factor productivity for primary and manufacturing industries.

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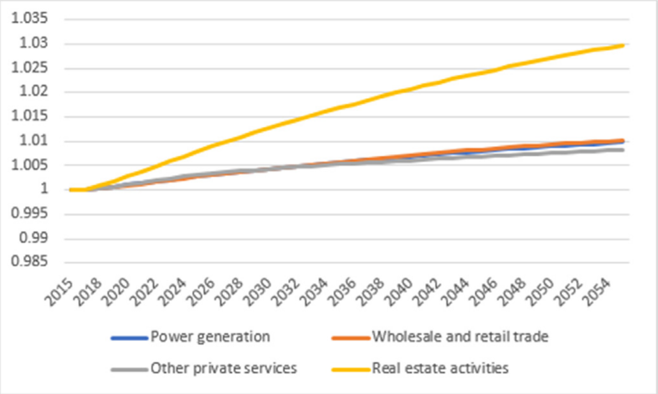
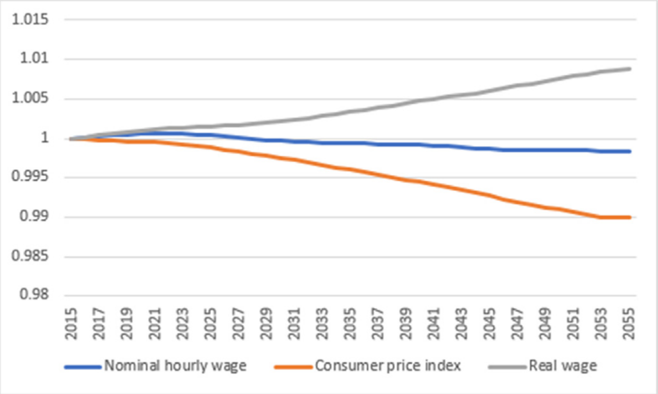
[18] This is defined as all industries except petroleum extraction, international shipping services and government.



Note: Model simulation of a negative shift in the user cost of R&D.

Fig. 7. Effects on total factor productivity for power generation and service industries.



Note: Model simulation of a negative shift in the user cost of R&D.

Fig. 8. Effects on nominal and real wages and the consumer price index.

affected is the low estimated spillover effect from domestic sources (see Tables 6 and 7).

For other private industries in the model, see Fig. 7, the effects on TFP are roughly similar except for Real estate activities. The result for the latter industry is due to the estimated spillover effect reported in Tables 6 and 7 which is larger for Real estate activities than for any other industry. So results for the “outlier industries” on Figs. 6 and 7, i.e. industries where the effect on TFP deviates much from one percentage point in the long run, follow from the estimates reported earlier. The Real estate industry also has relatively low R&D investments, which also follows from Table 8. Thus, policy that leads to increased R&D investments, could have higher spillover-effects for this industry. However, one should note that the real estate industry has had the slowest productivity growth, see Table 3.

The increase in TFP in these industries leads to a decrease in marginal costs which is why output prices and the consumer price index fall; see Fig. 8. The consumer price falls roughly in line with the increase in TFP. The nominal wage does not change much at all on average, so the consumer real wage increases. This is one factor behind the increase in household incomes that leads to higher consumption. On the other hand, total employment falls due to higher TFP as less employment is needed for the same level of production. This counteracts the increase in real wages. Consumption still increases, because transfers to households (mostly pensions) increase in real terms because pensions per pensioner are linked to the wage rate (a policy rule in Norway), and the number of pensioners is not reduced even if employment is.

From Table 11, we see that increases in TFP by industry lead to lower employment and higher unemployment. In the model, the hourly wage rate does not clear the labor market with constant unemployment in the long run, as is often the case in CGE/AGE models. Wage bargaining in Norway follows what is called “pattern bargaining” where bargaining in manufacturing sets a norm for wage growth that other industries follow. In manufacturing, profitability is the main factor driving wages, and the product real wage cost follows labor productivity. The level of unemployment also matters, while the consumer real wage does not matter in the long run. In our simulation, there is a larger productivity increase outside manufacturing. Thus, with wage changes mostly related to what happens to manufacturing and not the whole economy, this rigidity leads to wages not falling enough to bring unemployment back to the level in the reference scenario.

6. Conclusions

In this paper, we have studied the existence of spillovers from R&D investments that can motive a tax credit allowance system for R&D investment. We have analyzed the macroeconomic effects of tax policies related to R&D investment when there are spillovers from domestic as well as foreign sources of knowledge. We have done this by estimating a general dynamic econometric model of total factor productivity (TFP) by industry. Spillovers to Norwegian industries are not assumed to be a “free lunch” but depend on the industry's own knowledge as measured by its R&D capital stock. We found that both foreign and domestic sources of spillovers matter for TFP in most industries. At aggregate level we found that domestic R&D spillovers and increased skill intensity contributed 44 percent of the total growth in TFP in the period 1982 to 2018. The impact from international spillovers through technology adoption amounted to 38 percent. The remaining 18 percentage points are due to interaction effects. These results for Norway are in line with the findings in Coe et al. (2009).

Next, we extended a large-scale macroeconomic model by including these econometric TFP equations in the model and simulated the effects of a more R&D-friendly tax system. The policy change consists of a tax credit for R&D leading to a 23 percent decline in the user cost of R&D

Table 11
Macroeconomic effects of 23 percent permanent reduction in the user cost of R&D capital[a].

	5th year	10th year	15th year	20th year	25th year	30th year	35th year	40th year
Household consumption	0.0	0.1	0.2	0.3	0.5	0.6	0.8	1.0
Gross investment	1.0	1.0	1.3	1.7	2.0	2.2	2.5	2.8
- R&D investment	4.3	5.4	6.5	7.6	8.7	9.8	10.9	12.1
Exports, non-oil	0.0	0.1	0.2	0.4	0.5	0.7	0.8	0.9
Imports	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.7
GDP mainland	0.2	0.2	0.3	0.5	0.7	0.8	0.9	1.1
- Manufacturing	0.1	0.3	06	1.0	1.3	1.6	2.0	2.2
Employment mainland	0.0	−0.1	−0.2	−0.2	−0.3	−0.3	−0.4	−0.6
Unemployment rate, pp.	−0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
Real wage	0.0	0.1	0.2	0.3	0.5	0.6	0.8	0.9
Interest rate p.p.	0.0	−0.1	−0.2	−0.2	−0.2	−0.3	−0.3	−0.3

[a] Changes in percent unless otherwise stated. Note: Model simulation of a negative shift in the user cost of R&D.

capital. To counteract the loss in government revenues, estimated to be around EUR 200 million in 2018 or somewhat less than 0.1 percent of mainland GDP, we assume a cut in government transfers to households. We found that these policy changes lead to a substantial increase in R&D investment in the economy. As the R&D capital stocks gradually increase in various industries, they enjoy a spillover effect both from abroad and from domestic sources. In the short and medium term, the effects on aggregate output are very small, simply because the changes in capital stocks by industry are modest. However, after a decade, economic output increases and continues to grow so that the level of GDP increases steadily. At aggregate level, these effects are multiplied further, since productivity gains in the production of intermediate inputs lead to reduced input prices in downstream industries and thus a higher level of aggregate productivity through the Domar weighting scheme. This implies that the output growth rate is permanently higher due to the policy shift. Thus, the balanced budget multiplier is positive and increasing over time due to the supply side effects of stimulating R&D. After roughly 40 years, the levels of output, real wages and consumption are around one percent higher in our R&D tax policy scenario than in the baseline. The productivity gain leads to higher real wages and consumption. The size of these changes are small, but given the modest size of the policy change, the results show the potential importance of certain R&D policies. We have not calculated the potential welfare effects of the policy. To analyze welfare effects, and since productivity growth not only impacts the level of consumption, but also the level of employment, one should apply a model that captures the value of leisure and the disutility of work, possibly also including leisure externalities, see e.g. Pintea (2010). We leave this for future research.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: No competing interests. The project is financed by the Research Council of Norway, grant no. 256240 (OSIRIS).

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Appendix A. A description of other blocks in the KVARTS macroeconomic model

The macroeconomic model has an extensive input–output structure based on the National Accounts. All blocks in the model are determined simultaneously, which implies that a change in one industry will affect all the other industries. For each of the 38 products, there is a supply and use equation which, slightly simplified (by the dropping of the subscript for time), is given by[19]

$$X_p + I_p = A_p + \sum_k d_{pCk} C_k + \sum_a d_{pJa} J_a + \sum_s d_{pMs} M_s + DS_p = A_p + D_p, \tag{A1}$$

where p is an index for product, X_p is gross production, I_p is imports, A_p is exports, C_k is consumer category k, J_a is gross investment category a, M_s is category s of material input and DS_p is changes in total stocks. Total domestic demand, D_p, is thus the sum of consumption, gross investment, other material inputs and changes in total stocks. The indices k, r and j run over 15 consumer categories, 8 investment categories and 16 industries, respectively.[20] Finally, the symbols d_{pCk}, d_{pJa} and d_{pMs} denote fixed coefficients with values taken from the National Accounts.

Each imported good is assumed to be a variant of a composite domestically produced good. Each user minimizes the costs of consuming a composite good as in Dixit and Stiglitz (1977). Thus, the import share for each user of a composite commodity is a constant elasticity of substitution (CES) function of the domestic price (P_D) and the corresponding import price (P_I) for each commodity. Hence, total imports $I = \sum_p I_p$, where the imports of each commodity equal the import share multiplied by domestic demand

$$I_p = CES\left(P_{Ip} / P_{Dp}\right) \times D_p, \tag{A2}$$

Note that Eq. (A2) is slightly simplified compared with the actual model, as the structure of imports varies among domestic users. Thus, it is a weighted sum of the various components in Eq. (A1) that is inserted into Eq. (A2). The weights are taken from the most recent final National Accounts. For non-competitive imports, domestic production is zero or negligible and imports are given by demand. Exports ($A = \sum_p A_p$) are also assumed to be variants on the corresponding domestically produced goods and are modeled using the Armington approach[21]

$$A_p = G\left[\left(P_{Ap} / P_{Wp}\right) \times E, D_W\right], \tag{A3}$$

where the export price, P_{Ap}, relative to world market prices for similar goods (P_{Wp}) in domestic currency captures price effects and where E is an aggregate of the main exchange rates of relevance for Norwegian exports. The function G is multiplicative and homogeneous of degree zero in export and world market prices measured in a common currency. The world demand indicator (D_W), measured by aggregating the imports of Norway's main trading partners, captures income effects; see Boug and Fagereng (2010).

Consumption ($CONS$) is modeled in a three-step procedure. At the highest level, aggregate consumption in the long run is a log-linear function of real disposable income, DY, real wealth, $WEALTH$, and the after-tax real interest rate, rr,

$$\ln(CONS) = 0.85 \times \ln(DY) + 0.15 \times \ln(WEALTH) - 0.7 \times rr. \tag{A4}$$

Note that the coefficients of income and wealth sum to unity, i.e., consumption is homogeneous of degree 1 in income and wealth. The estimated aggregate consumption function is obtained from a cointegrated VAR system; see Jansen (2013) and Boug et al. (2021). At the next level, consumption is

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[19] We drop the subscript for time in this appendix.

[20] Note that the government sector has been aggregated in Table 2.

[21] For exports of crude oil and natural gas, gross domestic production is exogenous, and exports are determined by Eq. (A1).

spread over non-durable consumption, transportation vehicles and other durable consumer goods using a dynamic linear expenditure system based on the Stone-Geary utility function. At the lower level, expenditure on non-durable consumer goods is spread further in accordance with the Almost Ideal Demand System; see Deaton and Muellbauer (1980).

Prices are determined as mark-ups over marginal costs, where the latter is derived by minimizing the input cost per unit, given the production function. The producer price in every industry is determined by maximizing real profits, given that producers face a downward declining demand curve for their products on both domestic and export markets. Products are generally assumed to be imperfect substitutes; hence Norwegian product prices may differ from prices set by foreign competitors. Norwegian producers take foreign prices into account in their price setting in line with theories of monopolistic competition. In each industry, producer prices for domestic goods and exports (excl. taxes) are the product of mark-up (MU_p) and marginal cost (MC_p). Hence, producer prices excl. taxes (P) are determined as

$$P_p = MU_p \times MC_p. \tag{A5}$$

Standard theory (see for instance Rødseth, 2000, p. 266) tells us that the mark-up is a function of relative prices and total expenditure. We simplify and let each industry mark-up be a function of the relative price P_F/P:

$$MU_p = m_0 \times \left(P_{Fp}/P_p\right)^m, \tag{A6}$$

where P_F is the competing foreign price and m_0 and m are parameters. In the base year, when all price indices are one, MU equals m_0, so this parameter is the mark-up in the base year.

Inserting the expression for the mark-up in the price equation gives

$$P_p = m_0^{1/(1+m)} P_{Fp}^{m/(1+m)} MC_p{}^{1/(1+m)}. \tag{A7}$$

If $m = 0$, the mark-up is constant. In this case, price equals marginal cost multiplied by m_0. If, on the other hand, the export price or the price in domestic markets (m→∞) for each good equals the competitor's price, P_F, there is price-taking behavior and output (gross production) is determined by supply (small open economy case). Such price-taking behavior is the case in the petroleum industry where the crude oil price is exogenous in the model and all prices are equal (except for some short-run differences). In the standard case with mark-up pricing, output in each industry is determined by a weighted sum of the demand categories in the model. The empirical properties of the price equations are outlined in Boug et al. (2017). In addition to domestic price setting, foreign prices and taxes are essential in determining consumer prices. For each demand component, a purchasing price index is determined according to the structure in the National Accounts. The price index for other material inputs (P_{Mj}) by industry is used below as an example of how purchasing prices are determined

$$P_{Mj} = \sum_p c_p \left(1 + VAT_p\right)\left[\left(1 - IS_p\right)P_p + IS_p P_{Fp} + b_p ET_p + c_{tm} P_{TMp}\right]. \tag{A8}$$

The price index is a weighted sum of domestic (P) and foreign (P_{Fp}) basic prices, a trade margin (P_{TMp}) and excise taxes (ET_p), where the weights (denoted by lower case letters) are calibrated constants based on the National Accounts. IS_p is the import share for product i and VAT_p is the value-added tax rate, which varies according to uses.[22] The price indices for various consumer goods as well as investment categories are determined in the same way. Import prices are mostly exogenous and in foreign currency, although for some goods there are pricing-to-market effects; see Benedictow and Boug (2013).

The model also contains an exchange rate equation based on a combination of purchasing power parity and uncovered interest rate parity which links the Norwegian krone to the euro. The interest rate setting of the central bank is captured by a Taylor rule type of equation based on unemployment and inflation.

The employment block of the macroeconomic model consists of labor demand by industry, which can be aggregated to total labor demand, noting that employment in the government sector is exogenous. The total labor supply is disaggregated by age group (five age groups) and gender since participation rates vary substantially between groups and over time. In order to capture discouraged worker effects, we specify for each group a logit function relating labor supply in terms of the participation rate for each group to the (marginal) real after-tax wage as well as the unemployment rate. The logit function (g) by age group and gender generally reads

$$\ln\left(\frac{YP}{1 - YP}\right) = g[W \times (1 - TMW) \,/\, CPI, UR], \tag{A9}$$

where YP is the participation rate, W is the (average) wage, TMW is the (average) marginal tax rate on wage income, CPI is the consumer price index, and UR is the unemployment rate. The implied aggregated supply elasticity is in line with micro-econometric results in Dagsvik et al. (2013) and Dagsvik and Strøm (2006). The aggregate labor supply is found by multiplying the various participation rates by the size of the population in the corresponding group. Unemployment is merely the difference between the labor force (supply) and employment.[23]

The labor market is further characterized by large wage setters that negotiate on wages, given the price-setting behavior of firms (Layard et al., 2005). Unions are assumed to have preference for both wages and employment. Therefore, unions' bargaining power increases with low levels of unemployment, implying that the wage response is higher for a low level of unemployment than for a high level of unemployment. This non-linearity is captured in the specification of the wage curve:

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[22] Some services have a low rate, and some even have a rate equal to zero, but the standard VAT rate is 25 percent. Food has a low rate of 15 percent. Excise tax rates vary considerably across products: fuels, electricity, alcohol, tobacco and nearly all cars are heavily taxed, while most goods and consumer categories are hardly taxed at all. Both VAT rates and excise tax rates are exogenous variables in the model and are not changed in any of the simulations in our study compared to actual historical values.

[23] The model distinguishes between hours worked and employment, but we abstract from this distinction in the general overview.

$$\ln(W)+\ln(H)-\ln(P_Y)-\ln(Y)=f(UR), \tag{A10}$$

where H is hours worked, Y is the volume of value added and P_Y is the value-added price index. The left-hand side of the equals sign thus represents the wage share. The wage curve above mimics the wage-bargaining process in manufacturing. In Norway, wage growth in the manufacturing sector is the norm for wage growth in other sectors of the economy; see Aukrust (1977). This institutional setting is captured in KVARTS, and wages in the other sectors depend on wage growth in manufacturing, see Gjelsvik et al. (2020).

Appendix B. Definition of symbols used in appendix

Table B1
List of variables[a]

Symbol	Interpretation
X	Gross production
I	Imports
I_p	Imports of commodity category *p*
A	Exports
A_p	Exports of commodity category *p*
C_k	Consumer category
J_r	Gross investment category
M_s	Material input category *s*
DS	Changes in total stocks
D	Total domestic demand
d_{pCk}	Coefficient in supply and use equation related to consumption category
d_{pJr}	Coefficient in supply and use equation related to investment category
d_{pMs}	Coefficient in supply and use equation related to material input category
P_{Dp}	Domestic price of product *p,* which is also imported
P_{Ip}	Import price of product *p*
P_{Ap}	Export price in domestic currency of product *p*
P_{Wp}	World price of product of the same type as the export product *p*
E	Exchange rate index
D_W	Indicator of world demand
$CONS$	Total private consumption
DY	Total household real income
$WEALTH$	Total household real wealth
R	Real after-tax interest rate
P_p	Producer price exclusive of taxes for product *p*
MU_p	Mark-up for product *p*
MC_p	Marginal cost of product *p*
m_0	Parameter in mark-up equation (with unspecified product)
m	Parameter in mark-up equation (with unspecified product)
P_{Fp}	Competing foreign price (for unspecified product)
IS_p	Import share of product *p*
VAT_p	Value added tax for product *p*
P_{Mj}	Price of material inputs in industry *j*
P_{TMp}	Trade margin for material inputs related to product p
ET_p	Excise tax for product *p*
b_p	Coefficient attached to ET_p
YP	Participation rate (unspecified group)
TMW	Marginal rate on tax income
CPI	Consumer price index
UR	Unemployment rate
W	Wage per hour/hourly wage
H	Hours worked
Y	Value added, volume index
P_Y	Value added, price index
Symbol	**Interpretation**
Q_t	Sum of value added in industries with endogenized TFP in year *t*
P_{Qt}	Price index for the sum of value added in industries with endogenized TFP in year *t*
K_t^*	Sum of fixed and R&D capital in industries with endogenized TFP in year *t*
$P_{K_t^*}$	User cost of the sum of fixed and R&D capital in industries with endogenized TFP in year *t*
	User cost of R&D capital in year *t*
K_t^{RD}	Sum of R&D capital in industries with endogenized TFP in year *t*
$P_{K_t^{RD}}$	User cost of R&D capital in industries with endigenized TFP in year *t* year *t*
K_t	Sum of fixed capital in industries with endogenized TFP in year *t*
P_{K_t}	User cost of the sum of fixed capital in industries with endogenized TFP in year *t*
M_t	Sum of intermediate inputs in industries with endogenized TFP in year *t*
H_t	Sum of labor input in industries with endogenized TFP in year *t*
K_{jt}^*	Sum of fixed and R&D capital in industry *j*, $j \in J^1$
$P_{K_{jt}^*}$	User cost of the sum of fixed and R&D capital in industry *j*, $j \in J^1$

[a] Variables used in conjunction with Appendix E.

Appendix C. Derivation of user cost of capital and factor demand functions

The Lagrangian function for the firm's minimization problem can be written as:

$$\begin{aligned}L = \sum_{t=0}^{\infty}\beta^{t}\Bigg\{ & (1-\tau)[W_tH_t + P_{Mt}M_t] + P_t^J J_t + P_t^{J^{RD}} J_t^{RD} - \tau z_t^{RD} P_t^{J^{RD}} J_t^{RD} \\ & -\tau z_t^J P_t^J J_t - \tau_c P_t^{J^{RD}} J_t^{RD} - \lambda_{Xt}\left(X_t - f\left(TFP_t, K_{t-1}, K_{t-1}^{RD}, H_t, M_t\right)\right) \\ & -\lambda_{RD,t}\left(K_t^{RD} - (1-\delta^{RD})K_{t-1}^{RD} - J_t^{RD}\right) - \lambda_{Kt}(K_t - (1-\delta)K_{t-1} - J_t)\Bigg\}\end{aligned} \tag{C1}$$

The user cost of capital

The first-order condition with respect to R&D capital is:

$$\frac{\partial L}{\delta K_t^{RD}} = -\beta^t\lambda_{RD,t} + \beta^{t+1}\left(\lambda_{RD,t+1}(1-\delta^{RD}) - \lambda_{X,t+1}\frac{\partial X_t}{\partial K_t^{RD}}\right) = 0, \tag{C2}$$

which gives

$$\lambda_{Xt}\frac{\partial X_t}{\partial K_t^{RD}} = \beta^{-1}\lambda_{RD,t} - \lambda_{RD,t+1}(1-\delta^{RD}). \tag{C3}$$

The first-order condition with respect to R&D investments is:

$$\frac{\partial L}{\partial J_t^{RD}} = \beta^t\left(1 - z_t^{RD}\tau - \tau_c\right)P_t^{J^{RD}} + \beta^t\lambda_{RDt} \; or \; \lambda_{RDt} = -\left(1 - z_t^{RD}\tau - \tau_c\right)P_t^{J^{RD}}. \tag{C4}$$

Combining the two first-order conditions above, inserting the discount factor $\beta = \frac{1}{1+ir}$ and imposing the condition that the system is at a steady-state $(\lambda_{RDt} = \lambda_{RD,t+1})$ gives

$$-\lambda_{Xt}(1-\tau)^{-1}\frac{\partial X_t}{\partial K_t^{RD}} = P^{J^{RD}}\frac{1 - z_t^{RD}\tau - \tau_c}{1-\tau}(ir + \delta^{RD}), \tag{C5}$$

and with $z_t^{RD} = 1$, we have the user cost of capital for R&D as in Eq. (8).

Factor demand equations

The first-order condition with respect to labor $\partial L/\partial H_t = 0$ gives

$$-\lambda_{Xt}(1-\tau)^{-1}\frac{\partial X_t}{\partial H_t} = W_t. \tag{C6}$$

Combining the first-order condition for labor with that for capital yields the expression for the relative factor demands

$$\frac{\partial X_t/\partial K_t^{RD}}{\partial X_t/\partial H_t} = \frac{P_{Kt}^{RD}}{W_t}. \tag{C7}$$

Applying the Cobb-Douglas functional form of the production function and solving for each input yields the expressions for factor demands as provided in the main text.

Appendix D. Weights used for spillover aggregates

Table D1
Weights used for constructing capital aggregates across industries. w_{ji}.

j	i						
	1	2	3	4	5	6	7
1	0	0.4235	0.0471	0.0353	0.0824	0.0824	0.2000
2	0.3243	0	0.0541	0.0135	0.0541	0.0946	0.1892
3	0.0172	0.1897	0	0.0353	0.2069	0.1207	0.2759
4	0	0.0492	0.1148	0	0.0656	0.1311	0.5082
5	0.0103	0.0619	0.0103	0.0412	0	0.0309	0.7423
6	0	0.1087	0.0326	0.1413	0.0761	0	0.4348

(*continued on next page*)

Table D1 (*continued*)

j	i 1	2	3	4	5	6	7
7	0.0233	0.2093	0.0465	0.1860	0.0930	0.1395	0
8	0	0.0588	0.0588	0.0235	0.1176	0.0353	0.5176

j	i 8	9	10	11	12	13
1	0	0.0588	0	0.0706	0	0
2	0.0135	0	0	0.2432	0.0000	0.0135
3	0	0	0	0.0690	0.0172	0.0172
4	0.0492	0.0164	0	0.0164	0.0328	0.0164
5	0.0722	0.0206	0	0	0	0.0103
6	0.1957	0.0109	0	0	0	0.0000
7	0.1395	0.0465	0	0	0.0698	0.0465
8	0	0.1529	0	0	0	0.0353

Table D2
Weights used for constructing capital aggregates across industries. ww_{ji}

j	i 1	2	3	4	5	6
1	0	0.8889	0.0370	0	0.0370	0
2	0.3186	0	0.0973	0.0265	0.0531	0.0885
3	0.1212	0.1212	0	0.2121	0.0303	0.0909
4	0.0429	0.0143	0.0714	0	0.0571	0.1857
5	0.1111	0.0635	0.1905	0.0635	0	0.1111
6	0.1148	0.1148	0.1148	0.1311	0.0492	0
7	0.0447	0.0368	0.0421	0.0816	0.1895	0.1053
8	0	0	0	0.0750	0.1750	0.4500

j	i 7	8	9	10	11	12
1	0.0370	0	0	0	0	0
2	0.0796	0.0442	0.1770	0.0177	0.0354	0.0619
3	0.0606	0.1515	0.0303	0	0	0.1818
4	0.1143	0.0286	0.1429	0.0143	0.0143	0.3143
5	0.0635	0.1587	0.0794	0	0.0635	0.0952
6	0.0984	0.0492	0.1148	0.0164	0.0164	0.1803
7	0	0.1158	0.0553	0.0737	0.1684	0.0868
8	0.1500	0	0.0500	0	0.0250	0.0500

Appendix E. The Domar index

Domar (1961) and Hulten (1978) derived an equation corresponding to Eq. (18) in the current paper, but in contrast to us in continuous time. The aggregated gross product is given by

$$Q_t = TFP_t \times F\left(K_t^*, H_t\right) \tag{E1}$$

where $K_t^* = K_t + K_t^{RD}$ is the sum of fixed and R&D capital. For later use, we define the corresponding user cost by

$$P_{K_t^*} K_t^* = P_{K_t^{RD}} K_t^{RD} + P_{K_t} K_t.$$

We have the following accounting restrictions between the aggregated variables and the industry-specific variables:

$$Q_t = \sum_{j \in J^1} Q_{jt} = \sum_{j \in J^1} X_{jt} - \sum_{j \in J^1} M_{jt} = X_t - M_t, \tag{E2}$$

$$K_t^* = \sum_{j \in J^1} K_{jt}^* \tag{E3}$$

and

$$H_t = \sum_{j \in J^1} H_{jt}. \tag{E4}$$

Log-linearization of Eqs. (E1)-(E4) around their cost shares yields

$$\Delta\ln(TFP_t) \approx \Delta\ln(Q_t) - \frac{P^*_{Kt}K^*_t}{P_{Qt}Q_t}\Delta\ln\left(K^*_t\right) - \frac{W_tH_t}{P_{Qt}Q_t}\Delta\ln(H_t), \tag{E5}$$

$$\Delta\ln(Q_t) \approx \sum_{j\in J^1}\frac{P_{X_{jt}}X_{jt}}{P_{Qt}Q_t}\Delta\ln\left(X_{jt}\right) - \sum_{j\in J^1}\frac{P_{M_{jt}}M_{jt}}{P_{Qt}Q_t}\Delta\ln\left(M_{jt}\right), \tag{E6}$$

$$\Delta\ln\left(K^*_t\right) \approx \sum_{j\in J^1}\frac{P_{K^*_{jt}}K^*_{jt}}{P_{K^*_t}K^*_t}\Delta\ln\left(K^*_{jt}\right) \tag{E7}$$

and

$$\Delta\ln(H_t) \approx \sum_{j\in J^1}\frac{W_{jt}H_{jt}}{W_tH_t}\Delta\ln\left(H_{jt}\right) \tag{E8}$$

where we in conjunction with Eq. (E5) have assumed a scale elasticity of one and perfect competition such that valued added in nominal terms $P_{Q,t}Q_t$ equals the costs of all input factors, that is

$$P_{K^*_t}K^*_t + W_tH_t + P_{M_t}M_t.$$

Correspondingly, we can replace the nominal value of value added in Eq. (E5) with the cost of all factors (or multiply it with the reciprocal of the mark-up in Eq. (A5)).

Inserting Eqs. (E6)-(E8) into Eq. (E5) yields Eq. (18), where

$$\Delta\ln\left(TFP_{jt}\right) \approx \Delta\ln\left(X_{jt}\right) - \frac{P_{K^*_{jt}}K^*_{jt}}{P_{X_{jt}}X_{jt}}\Delta\ln\left(K^*_{jt}\right) - \frac{W_{jt}H_{jt}}{P_{X_{jt}}X_{jt}}\Delta\ln\left(H_{jt}\right) - \frac{P_{M_{jt}}M_{jt}}{P_{X_{jt}}X_{jt}}\Delta\ln\left(M_{jt}\right), \tag{E9}$$

which is the equation that forms the basis of our construction of the-industry-specific TFP indices; see Eq. (19).

Appendix F. Additional estimation results

Table F1
Diagnostics for the estimated equations.

Industry	R^2	DW	LM test for heteroscedasticity[a]
1	0.867	2.391	0.799
2	0.306	2.219	0.480
3	0.283	2.071	0.581
4	0.327	2.148	0.937
5	0.863	2.198	0.650
6	0.823	1.860	0.163
7	0.713	2.551	0.774
8	0.413	1.880	0.032

[a] Significance probability. The null hypothesis implies absence of heteroscedasticity.

Table F2
Scaled estimated covariance matrix of the errors in the system of regression equations[a]

Industry	Industry							
	1	2	3	4	5	6	7	8
1	11.7416							
2	0.0853	0.0714						
3	0.0028	0.0269	0.1575					
4	−0.4513	0.0151	−0.0129	0.1527				
5	−2.0109	−0.0095	0.0061	0.0465	3.2474			
6	−0.3928	0.0259	0.0413	0.0429	0.1648	0.2518		
7	0.5515	0.0314	0.0233	0.0127	−0.1246	0.0296	0.2366	
8	−1.8860	0.0372	0.0093	0.0632	0.0972	0.1231	0.0991	1.8864

[a] The estimated covariance matrix, $\widehat{\Omega}$, has been multiplied by 1000.

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