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Abstract
Evidence points to relatively low supply elasticities for workers skilled for research and development (R&D), which can hamper innovation and growth. Increasing the supply of R&D skills will expand an economy's innovative capacity. A simultaneous effect of increased education, which is particularly important for small, open economies, is to raise final goods producers' capacity to absorb cross-border knowledge spillovers. In a calibrated endogenous growth model for Norway, we find that increasing the share of highly educated workers has pronounced absorptive capacity effects that partially crowd out R&D-based innovation. Both innovative and absorptive capacity expansions contribute to higher growth and welfare.

Keywords: Absorptive capacity, Computable general equilibrium model, Endogenous growth, Human capital, Innovation, Research and Development

JEL classification: O30, O41

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1. Introduction

In the pioneering endogenous growth models by Romer (1990a,b) and Aghion and Howitt (1992), human capital levels are an important driver of productivity growth. Along with the efforts of most governments over the last decades to stimulate research and development (R&D), there has been a growing concern for an apparent shortage of researchers and a relatively scarce enrolment of students with the relevant university degrees. In the European 2020 smart growth strategy[1], targets for higher educational attainments and improved academic institutions are central. It is argued that intensified R&D activity, which is the main engine of technological change and economic growth, is hampered by a lack of human capital resources. As illustrated in theoretical models with R&D-specific skills by Arnold (1999) and Grossman (2007), this situation occurs when the resources used by the R&D industry are inelastic in supply. They show that in this case, the most effective growth policy is to increase their availability.

The empirical issue remains as to what extent an increased supply of high-skilled labor will serve to increase the *innovative capacity* of an economy (Furman et al. 2002) rather than be soaked up by other, high-skill intensive industries. The latter is not necessarily a detriment to economic growth. A large strand of the growth literature points to the *absorptive capacity* effects of increased education (Benhabib and Spiegel 1994; Keller 2004). Human capital is vital for a country's ability to absorb cross-border knowledge spillovers from the international technology frontier through imitation (Acemoglu et al. 2006; Vandenbussche et al. 2006).

In this study, we ask whether and through what mechanisms increasing the share of highly educated (high-skilled) labor spurs growth in a small, open economy. We employ an endogenous growth model calibrated to the Norwegian economy. High-skill intensive R&D activity drives growth as modeled in Romer (1990) and has been adopted in several existing applied growth models; see Diao et al. (1999), Russo (2004), Ghosh (2007), and Bye et al. (2009). However, the empirical evidence shows that cross-border spillovers are more important for growth in small, open economies, such as Norway (Coe and Helpman 1995). The main contribution of our analysis is a special focus on the absorptive capacity effects of human capital and how they interplay with (the more frequently addressed) innovation effects.

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[1] http://ec.europa.eu/europe2020/index_en.htm

Innovative capacity constraints by lack of human capital are supported by some scientific evidence. Goolsbee (1998) and Wolff and Reinthaler (2008) find relatively low supply elasticities for R&D workers in the US and OECD countries, respectively. Machin and McNally (2007) conclude that the under-supply of relevant tertiary education is an issue in most countries, and Salvanes and Førre (2003) document that labor supply and demand development in the small, open Norwegian economy resembles that of most other OECD countries.

Benhabib and Spiegel (1994) argue that the most important role of human capital is as a facilitator of technological dispersion. Similar results appear in Borensztein et al. (1998) and Lutz et al. (2008). This argument implies that human capital has ‘a second face’, as originally suggested by Nelson and Phelps (1966) and formally modeled in a general framework by Eicher (1999). This hypothesis is supported by later studies that include both R&D-based knowledge and human capital as absorptive capacity determinants (Griffith et al. 2004; Crespo et al. 2004; Madsen et al. 2010).

Our model replicates the empirically observed industrial variation in factor intensities and international trade intensities. These intensities are decisive for the resource reallocation and productivity growth processes taking place in response to the inflated share of highly educated workers. One of the main growth channels, the *innovative capacity* channel, is initially fueled by a relative expansion of the high-skill intensive R&D industry, which is caused by the Rybczynski effect (Rybczynski 1955). Boosted production of patents and patent-based, high-tech capital spurs technological change. The patent-based technology in our model is universal and can be adopted by industries with various factor compositions. As increased high-tech production coincides with an increase in the high-skilled share of the economy, high-tech investments will tend to take place in final goods industries that combine high-tech intensity with high-skill intensity. This effect is analogous to the skill-biased or skill-directed technological change first introduced in Berman et al. (1994) and explored further in Acemoglu (1998) and Kiley (1999) in simple frameworks, with two R&D-based technologies complementing either low or high skills.

The other main channel through which education shifts spur growth, the *absorptive capacity* channel, is modeled in relation to firms’ international trading. While earlier studies focused primarily on the import channel, we also include export as a channel for absorption in accordance with relatively new empirical evidence; see Delgado et al. (2002), Baldwin and Gu (2003), Alvarez and Lopez (2008).[2] The ab-

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[2] Another potential channel for spillovers is foreign direct investments (FDI). We exclude FDI as a channel, based on two Scandinavian studies (Grünfeld 2002;

sorptive capacity of an economy is spurred both by R&D intensity and the human capital level of firms involved in international trading.

Our growth model features diminishing returns to innovation, as in Jones (1999), and to absorption, in line with the knowledge gap assumption (Griffith et al. 2004; Acemoglu et al. 2006; Vandenbussche et al. 2006). Thus, the growth effects of extending the share of skilled workers are transitional. A political motivation for stimulating the transitional growth dynamics is the positive externalities associated with both R&D and absorption. These features include a *standing-on-shoulders effect* (Romer, 1990), which refers to the continuous productivity growth within the R&D industry caused by dynamic spillovers from accumulated R&D knowledge stock. Patent production in the R&D industry also generates an external *love-of-variety effect*: the productivity of R&D-based high-tech capital used within final goods industries increases with the number of patents/varieties. Finally, the *endogenous absorption* of spillovers from abroad involves externalities, as improvements in absorbed productivity at the firm level depend on the entire industry's extent of foreign trade and absorptive capacity. The latter effect is especially important for small, open economies.

We find that increasing the share of highly educated labor has significant effects on both imitation of international technologies and development of domestic patents, i.e., both absorptive and innovative capacities expand. If the absorptive capacity effect is sufficiently strong, education policies can even cause R&D activity to fall. Both innovation and imitation processes contribute to higher growth and welfare. Contrary to the results in Acemoglu (1998) and Kiley (1999), which are based on models of closed economies, we find that long-run domestic innovation is not particularly biased towards high-skill intensive industries. The imitation process soon dominates and directs resources, including domestically developed technologies, to trade intensive industries, which are not especially high-skill intensive.

Section 2 describes the model with particular emphasis on innovation and absorption effects, while Section 3 presents policy and sensitivity analyses. Concluding remarks are given in Section 4.

Braconier et al. 2001) that find no significant spillover effects from inward FDI. However, the findings in the literature are mixed. Pottelsberghe and Lichtenberg (2001) do, for example, identify spillovers from FDI on the macro level, while Damijan et al. (2004) find that spillovers through inward FDI stands out as the most important contributor to productivity in 10 transition economies, based on firm-level data.

2. An open economy CGE model with innovation and absorption effects

2.1 General features

We use a dynamic CGE model with intertemporally optimizing firms and households. The model fits a small, open economy and is calibrated to the Norwegian economy. It specifies 13 final goods industries and one R&D industry producing patents and patent-based, high-tech capital goods. The public sector collects taxes, distributes transfers, and purchases goods and services from the industries and from abroad. International prices are determined by the world market, as is the interest rate.

There are two, imperfectly substitutable labor types: highly educated (high skilled) and low skilled.[3] Highly educated is defined as having more than four years of university education or the equivalent. All industries use both skill types but differ greatly in their intensities. Patent production in the R&D industry is the most high-skill intensive industry (see Table 1).

Productivity growth in the model derives from two channels: domestic innovation and international spillovers. Domestic innovation processes have their origins in the R&D industry, where high-skilled labor is an important input. International spillovers are especially pronounced in the final goods industries and depend on the industries' high-tech capital intensity, use of high-skilled labor, and trade intensities. In the next two subsections (2.2 and 2.3), we present the two productivity growth channels. Subsection 2.4 briefly describes the rest of the model.[4]

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[3] Each of the labor types is perfectly mobile within the country but immobile across borders.

[4] Transfers, and tax and subsidy wedges are suppressed in the present exposition. Appendix B provides a more thorough, aggregated presentation of the equations determining firm and household behavior. Appendix C gives details on parameter values, as well as calibration and solution procedures. Bye et al. (2006) provides a thorough documentation of the model.

Table 1: Factor intensities of value added, selected private industries, 2002

	High-skilled labor	Low-skilled labor	High-tech capital	Other capital
R&D industry				
- Patent production	0.60	0. 25	-	0.14
- High-tech production	0.05	0.83	-	0.13
Consumer goods and services	0.04	0.79	0.02	0.15
Traditional manufacturing	0.04	0.55	0.05	0.36
Ordinary machinery	0.05	0.82	0.02	0.11
Construction	0.01	0.92	0.01	0.07

2. 2 Productivity growth through absorption of international knowledge

In general terms, the technology of firm *i*, irrespective of industry, can be represented by

$$(1) \qquad X_i\left(X_i^H, X_i^W\right) = g_i\left(VF_i\right).$$

where X_i^H, X_i^W represent production for domestic and export deliveries, respectively, and VF_i is a nested Constant Elasticities of Substitution (CES) function containing a number of variable inputs (see Figure B.1 in Appendix B). The simplified version of VF_i can be represented by[5]

$$(2) \qquad VF_i = \tau f_i\left(L_i^H, L_i^L, K_i^V, K_i^M, V_i\right).$$

where L_i^H , L_i^L K^V_i, K^M_i, and V_i represent the firm's input of high-skilled labor, low-skilled labor, high-tech capital, other capital, and intermediates, respectively. Factor inputs also depend on a factor-neutral, endogenous productivity level τ, which is common to all firms in the industry and, as such, has no subscript. We assume that the growth in τ is partly exogenous and partly dependent on the endogenous industry-specific capacity to absorb spillovers from abroad.

$$(3) \qquad \dot{\tau} = \dot{\tau}^* + (\lambda_1 A + \lambda_2 B)\Delta.$$

The first term, $\dot{\tau}^*$, is the exogenous growth driver, while the second term expresses the productivity growth that depends on endogenous

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[5] A more accurate and specified representation of the product function, which exhibits decreasing returns to scale, is given in Appendix B.

export and import impetuses, represented by the terms A and B, as well as on the productivity gap, Δ, from the exogenous frontier, τ^F; i.e., $\Delta = (\tau^F - \tau)/\tau^F$; see, e.g., Griffith et al. (2004). The literature is mixed regarding the strength of the export and import impetuses, and we assume that $\lambda_1 = \lambda_2$.

Based on empirical findings in Alvarez and Lopez (2008), Coe and Helpman (1995), and Griffith et al. (2004), we model endogenous absorption through both an export channel labeled A and an import channel labeled B, defined as follows:

$$(4) \qquad A = \Omega^H \cdot \Omega^R \cdot \frac{X^W}{X},$$

$$(5) \qquad B = \Omega^H \cdot \Omega^R \cdot \frac{I}{X^H}.$$

The term A accounts for the absorbed productivity's dependence on industry exports, X^W, as a share of the total output, X. The term B describes the corresponding dependence on industry imports, I, measured relative to the domestic deliveries of similar products from domestic firms within the industry, X^H. The functions Ω^H and Ω^R represent the absorptive capacity of the firm from high-tech capital and human capital in the industry, respectively. We model Ω^R as a function of the industry's input intensity of high-tech capital $\kappa^R = K^V / VF$ and Ω^H as a function of the industry's input of high-skilled labor, L^H, both normalized to the base year level:

$$(6a) \qquad \Omega^R = \frac{\varphi \kappa^R}{\frac{\varphi}{2} + \kappa^R}, \qquad \varphi > 0,\ \Omega^{R'} > 0,\ \Omega^{R''} < 0.$$

$$(6b) \qquad \Omega^H = \frac{\varphi L^H}{\frac{\varphi}{2} + L^H}, \qquad \varphi > 0,\ \Omega^{H'} > 0,\ \Omega^{H''} < 0.$$

The model implies that for industries engaging in foreign trade, firms' capacities to learn from this interplay with foreign agents expand if human capital or the intensity of high-tech capital within the industry increases, though with decreasing returns. The estimates and calibration procedures are described in Appendix C.

All firms are symmetric, and we implicitly assume that they do not consider the strategic effects of adjusting their trade on their absorbed productivity, high-tech capital intensity, or input of high-skilled labor , as the firms are small. Thus, the absorbed productivity effects are external.

2.3 Productivity growth through domestic innovation

Domestic innovation takes place within the R&D industry, which then provides high-tech technologies. The process involves two distinct activities within each firm: (i) R&D that develops patents and (ii) capital production based on these patents, or high-tech capital. Industry output of patents, X_R, benefits from endogenous domestic productivity spillovers due to an accumulated stock of knowledge (the standing-on-shoulders effect), *R*, and are freely accessible, thus

$$X_R = R^{s_1}\tau^{*}VF^{\,s} \tag{7}$$

and $R = R_{-1} + X_R$. The parameter s_1 denotes elasticity with respect to domestic spillovers. As suggested in Jones (1995), it is less than unity. The productivity growth dynamics generated by the accumulated stock of R&D knowledge, *R*, is external to the individual patent producer, who is too small to consider the effect of its own output on the accumulated stock of patented knowledge. $s < 1$ is the scale elasticity of the variable input factors used for production of R&D. The R&D industry also benefits from spillovers from abroad through interactions with researchers internationally, journal articles, patents, etc. These spillovers are considered exogenous and are represented by τ^*. The development of a patent represents a fixed establishment cost for a new firm in the R&D industry before entering the market for high-tech capital goods with a new and distinct variety, K^V. The production of high-tech capital varieties also involves variable factor input costs.[6] We assume identical factor input cost structures for all R&D firms, both in their patents and in their high-tech capital production.

High-tech capital varieties are partly exported and partly delivered to domestic final goods industries.[7] The input of each high-tech capital variety in final goods industries is represented by Spence-Dixit-Stiglitz (love-of-variety) preferences for a composite of the varieties, K^V:

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[6] There are decreasing returns to scale, and the common scale elasticity also applies to R&D activity; see more details in appendices B and C.

[7] In the R&D industry, the input of K^V is per definition zero in both R&D activity and R&D-based capital production to avoid cumulative love-of-variety multiplicators. Note that there are, thus, no absorptive capacity effects through R&D-based investments in the R&D industry.

$$(8) \qquad K^V = \left[\sum_{i=1}^{R} \left(K_i^V\right)^{(\sigma_{KV}-1)/\sigma_{KV}} \right]^{\sigma_{KV}/(\sigma_{KV}-1)}.$$

The accumulated stock of R&D knowledge, R, also represents the number of firms in the R&D industry and of available patented varieties. σ_{KV} is the uniform elasticity of substitution that is applied to all pairs of capital varieties. It is common to all final goods industries. The more varieties there are, the higher the productivity of high-tech capital within the final goods industries. This love-of-variety effect represents a second external productivity growth mechanism stemming from R&D that benefits the final goods firms, particularly those in high-tech intensive industries. Again, the R&D firms are too small to consider their impact on the productivity of the aggregated composite, K^V. The input intensity of the high-tech capital composite within a final good industry j, K_j^V / VF_j, varies with j and reflects the high-tech capital channel of absorptive capacity.

2.4 Other market behavior, equilibrium, and balanced growth

2.4.1 Market behavior of firms

Final goods industries[8] deliver to final markets and produce intermediates for each other according to an empirical input-output structure based on the 2002 National Accounts. Production for each identical firm is allocated to foreign and domestic markets, which are segmented through a Constant-Elasticity-of-Transformation (CET) technology.

$$(9) \qquad X_i = \left[\left(X_i^H\right)^{\rho} + \left(X_i^W\right)^{\rho}\right]^{1/\rho}.$$

The transformation elasticity $\rho > 0$ implies the costs of diverting deliveries between the two markets.[9] By assuming $\rho = 1/s$, we obtain separability between export and home market supplies; see Holmøy and Hægeland (1997). Each firm has perfect foresight and maximizes the present value of the after-tax cash flow. For final goods industries, we assume perfect competition among numerous firms within each industry, and first-order conditions equate prices with marginal costs within the two segmented markets. CET technology implies that the ratio of

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[8] See appendix A for a list. The Public Sector, as well as the Ocean Transport, Oil and Gas Explotation, and Drilling Industry are treated exogenously

[9] This, together with decreasing returns to scale for total factor use such that $s < 1$, avoids complete specialization of tradable production.

export to domestic market deliveries is determined by the relative price between them.

R&D firms exhibit market power in the domestic market for high-tech capital. Maximization of the present value of the after-tax cash flow gives the following first-order conditions for deliveries to the home market X_{Ki}^{H} and export market:

$$(10) \qquad P_{Ki}^{H} = m_{Ki}\frac{c}{s}\left(X_{Ki}^{H}\right)^{\frac{1-s}{s}},$$

$$(11) \qquad P_{K}^{W} = \frac{c}{s}\left(X_{Ki}^{W}\right)^{\frac{1-s}{s}}.$$

The monopoly price of high-tech capital variety *i*, P_{Ki}^{H}, is set as a mark-up, m_{Ki}, on costs. $m_{Ki} = \frac{\varepsilon_{Ki}}{\varepsilon_{Ki} - 1}$, where ε_{Ki} is the domestic demand elasticity for high-tech capital varieties equal to σ_{KV}. The price in the domestic market is equal for all high-tech capital varieties, and each variety is produced in equal quantities. The marginal costs of export deliveries equal the exogenous world market price of capital varieties, P_{K}^{W}.

Based on value maximization for the representative firm and the fact that profit is equal for all firms, the entry condition for each R&D firm in capital variety markets can be deduced as

$$(12) \qquad \mathrm{P}_{\mathrm{R}0} = \int_{0}^{\infty} \mathrm{e}^{-\mathrm{rt}}\left(\bar{\pi}_{\mathrm{t}}\right)\mathrm{dt}.$$

P_{R0} is the fixed entry cost in period 0 or the shadow price of developing a patent in advance of variety production. Firms enter until the representative firm's discounted net profits $\bar{\pi}_t$ equal the entry cost. In each period, new patents are produced and new firms will enter the R&D industry. Given that a firm has entered, the first-order condition in eq. (10) determines the domestic price of high-tech capital variety for given marginal costs and demand.

Except for the two types of labor and high-tech capital, the factors of production are importable. An Armington type CES aggregate of imported and homemade varieties of the same investment or intermediate good defines them as imperfect substitutes, implying the following purchaser price, *P*, of a composite good:

$$(13) \qquad P = \left((1-\upsilon)(P^{H})^{(1-\sigma_{HI})} + \upsilon(P^{I})^{(1-\sigma_{HI})}\right)^{\frac{1}{1-\sigma_{HI}}}.$$

P^H is the price of the domestic variety, P^I is the respective, exogenous, import price, ν is the initial import share, and σ_{HI} is the substitution elasticity (Armington elasticity) between the two varieties. The Armington assumption implies that the shares of imports to home deliveries are determined by the ratio of domestic to import prices.

2.4.2 Consumer behavior

Consumption and savings result when the decision of an infinitely lived, perfectly foresighted and representative consumer maximizes intertemporal utility. The consumer chooses a consumption path subject to an intertemporal budget constraint that requires the present value of consumption not to exceed total wealth (current non-human wealth plus the present value of labor income and net transfers). Total consumption is allocated across 10 different goods and services according to a nested CES structure (see Figure B.2 in Appendix B). Each consumer good also consists of one imported and one domestically produced variety according to an Armington function analogue to eq. (13). The representative consumer supplies high- and low-skilled labor in exogenous amounts.

2.4.3 Equilibrium conditions

The model is characterized by equilibrium in each period in all product and labor markets.

Intertemporal equilibrium requires fulfillment of two transversality conditions: the limit values of the total discounted values of net foreign debt and real capital must be zero. The model is characterized by a path-dependent, balanced growth path solution (or steady state solution); see Sen and Turnovsky (1989) for a theoretical exposition. This model implies that both the path and the long-run stationary solution differ across simulated scenarios.

To ensure a long-run, *balanced growth path*, the following conditions must be fulfilled: *1)* the rate of technological change for each input factor in each industry must converge to the same rate, *g*, such that each industry grows at the same rate, *2)* growth in per capita consumption equals *g*, and *3)* the population growth rate is constant. Along the transitional path, the growth rate may vary. Bye et al. (2006) provide further details.

A balanced growth path also requires that the following equation is fulfilled:

$$(14)\qquad \left[\frac{(1+\theta)}{(1+r)\big/(1+p)}\right]=(1+g)^{-1/\sigma_d}$$

where θ is the rate of time preferences, r is the nominal interest rate, p is the growth rate of the consumer price index, and σ_d is the intertemporal elasticity of substitution. Together with equation (14), the transversality condition regarding net foreign debt is fulfilled when the consumer finds the optimal level of consumption, given the intertemporal budget constraint and the transversality condition. Correspondingly, the transversality condition for the value of real capital is a restriction on the determination of net investments by firms. In an infinite time horizon, growth in our model will only depend on exogenous drivers. For technical reasons, we have set all exogenous and endogenous growth drivers to zero in the far future (after approximately 100 years). This setting ensures that the economy is eventually on a balanced growth path (steady state) and that this growth path, with zero growth in both consumption and the consumer price index, satisfies these transversality conditions. In particular, equation (14) then implies that $r=\theta$ at all points in time.

3 A shift in the share of high-skilled labor

We implement an exogenous, unanticipated increase of 20 per cent in the share of high-skilled labor in the private sector. This increase can be broken down into an increase of 21 per cent in the supply of high-skilled labor and a fall of 1 per cent in the supply of low-skilled labor to the private sector. High-skilled workers are defined as having more than four years of university education or the equivalent. Implicitly, the added stock of highly educated workers possesses the same skill-composition as those high-skilled workers already employed in the private sector. In the base year, 2002, approximately 60 per cent of highly educated workers in the private sector were scientists and engineers. This share also corresponds to the composition within private R&D research institutes and firms; Research Council Norway (2009). This simulated shift is therefore relevant for studying an increased supply of R&D-skills.

The impacts on productivity and growth can best be understood by tracking reallocations and changes in industrial patterns that take place and how they affect the two main growth mechanisms, innovation and absorption (or imitation). The immediate effect of increasing the high-skill share is a more productive labor force, particularly in skill-intensive industries. In line with the Rybczynski theorem (Rybczynski, 1955), high-skilled labor will substitute for low-skilled labor in all industries and high-skill intensive industries will expand in relative terms. As the R&D industry is highly skill-intensive, the increased share of highly educated labor will increase the *innovative capacity* of the economy. More R&D will initiate a productivity boost by stimulating investments of R&D-based capital in final goods industries. The simultaneous incidence of expanded production of universal high-tech capital and an increased supply of high-skilled workers implies that technological improvements tend to be biased towards high-skilled labor, or more precisely, towards final goods industries that combine high-tech intensity with high-skill intensity. Finally, the use of high-tech capital as well as the direct increase in the number of high-skilled labor (human capital) will improve the *absorptive capacity* for knowledge spillovers through trade, which also affects the ways in which technological progress occurs and contributes to overall economic growth.

We compare the shift in the high-skilled share with a similar shift in a reference model that leaves out absorptive capacity effects. This reference scenario is constructed to separate the effects of increased education on innovative capacity from those directly affecting absorptive capacity. Finally, we perform a sensitivity analysis where the absorptive capacity effect of human capital is reinforced from its calibrated level (see Section 2.2).

Our model replicates the empirically observed industrial variation in trade intensities and factor intensities, as mirrored in Table 1. In addition to some economy-wide effects, Table 2 reports effects on output, resource flows and productivity for selected, representative industries: the R&D Industry, which is the most *high-skill intensive* industry in the economy; the Consumer Goods and Services industry, which is relatively *low-skill intensive*; and the Traditional Manufacturing industry, which is relatively *high-tech intensive* in addition to being *trade-intensive*. The trade intensity of this industry measured as gross trade relative to gross product amounts to more than 2.[10] The effects in all scenarios are measured as percentage changes from a benchmark scenario that uses the benchmark calibrated labor composition (see Section 2.1 and Appendix B).

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[10] Gross trade of good *i* is the sum of gross exports and gross imports of good *i*.

Table 2. Industrial output and resources, percentage changes from benchmark, long run

	Scenarios		
	Reference	**Main**	**Sensitivity**
High-skill intensive:			
R&D Industry			
Patent production	19.3	15.5	-24.7
High-tech production (domestic deliveries)	6.1 (7.5)	5.3 (7.9)	-17.7 (-7.6)
High-skilled in patent production	23.8	20.7	-14.7
High-skilled in high-tech production	24.5	21.9	0.2
Absorbed productivity	-0.1	1.0	-0.7
Low-skill intensive:			
Consumer Goods and Services			
Production	0.5	1.7	2.0
High-skilled	18.6	18.3	23.9
High-tech capital	6.5	5.4	-10.5
Absorbed productivity	0.8	2.1	1.2
High-tech and trade intensive:			
Traditional Manufacturing			
Production	3.6	6.9	7.5
High-skilled	21.5	23.7	30.2
High-tech capital	9.4	10.5	-5.7
Absorbed productivity	1.5	2.8	2.3
Economy-wide effects			
GDP	2.1	3.9	1.0
Average absorbed productivity	1.0	3.0	2.9
Education premium	-8.8	-8.9	-10.1
Number of patents/high-tech varieties	11.7	8.6	-16.3
Price per efficiency unit of high-tech capital	-4.9	-3.3	2.3
Welfare*	0.6	1.7	2.3

* Percentage change in discounted value of consumption.

3.1 The reference scenario: No absorptive capacity effects of human capital

As observed in Table 2, the Rybczynski effect is evident through a considerable up-scaling of the *high-skill intensive* R&D Industry. The effect expands production of patents by 19.3 per cent and of high-tech capital by 6.1 per cent. In addition to the favorable effect of the increased high-skilled supply, the R&D industry faces positive productivity externalities from standing on the shoulders of previous R&D efforts, as a result of the observed 11.7 per cent increase in the number of R&D firms/patents.

The relative expansion of the high-skill intensive industries is mirrored by a fall in the education premium for highly educated workers, which in the long run amounts to -8.8 per cent. The industries most adversely affected by wage changes are relatively *low-skill intensive* industries, represented in Table 2 by Consumer Goods and Services.[11]

As high-tech capital is universally applicable, the combination of increased R&D and increased high-skill availability can potentially lead to a high-skill biased technological change in the final goods sector, as demonstrated in the theoretical models of Acemoglu (1998) and Kiley (1999). However, the final goods sector in this calibrated model is far more complex. The industries' variation in high-tech intensity is empirically more decisive for technological direction than their much smaller variance in high-skill intensity. We find that R&D-based technological change first benefits *high-tech intensive* industries, as shown by the expansion of Traditional Manufacturing. This industry benefits from technological progress through a higher quantity *and* quality of its investments in high-tech capital. The delivered quantity of high-tech production for the home-market amounts to 7.5 per cent; the relative increase of high-tech input in Traditional Manufacturing is 9.4 per cent. This quality increase is due to the love-of-variety effect, which causes the price per efficiency unit of high-tech capital to drop by 4.9 per cent in the long run.

The absorption processes in the reference scenario are fuelled only by increased high-tech intensities and do not directly benefit from an increased supply of high-skilled labor. Nevertheless, we find a significant increase in absorbed productivity. As *high-tech-intensive* industries, most prominently Traditional Manufacturing, tend to be *trade-intensive*, absorbed productivity increases. In Traditional Manufacturing, absorbed productivity rises by 1.5 per cent, while average absorbed productivity increases by 1 per cent in the long run. Note that

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[11] Table 1 presents direct factor intensities. The input-output modified intensities are more relevant in explaining the Rybczynski and reallocation effects. These, however, are not easily quantified in a complex CGE model.

the absorption process is self-enforcing as higher productivity increases export, which further increases absorbed productivity. *High-tech intensive* industries, therefore, enjoy both innovation and imitation-based productivity growth, which explains a 3.6 per cent increase of output in Traditional Manufacturing,

3.2 Main scenario: Innovative and absorptive capacity effects of human capital

In the main scenario, we use the complete model where a highly educated population also has a direct absorptive capacity effect, so that increasing the share of high-skilled labor enables the economy to gain even more from cross-border productivity spillovers. The result is an industrial pattern more biased towards *trade-intensive* industries than the pattern in the reference scenario.

As Table 2 shows, a larger amount of highly educated labor now flows towards the *trade-intensive* Traditional Manufacturing industry. This shift comes at the expense of the *high-skill intensive* R&D industry but also draws resources from the *low-skill intensive* Consumer Goods and Services industry. The result is a relative fall in the output of patents when compared with the reference scenario. A lower number of patents implies a smaller productivity gain for R&D firms from standing on the shoulders of previous R&D efforts. This fall in patents also results in a smaller love-of-variety improvement in the quality of high-tech capital within final goods industries.

High-tech capital output also falls when compared with the reference scenario. However, weaker innovation effects are partly compensated by a slightly larger increase in deliveries directed to home markets. We find a marked shift in the direction of domestic deliveries of R&D-based technology towards the *trade-intensive* industries. This technological bias was also found in the reference scenario, but it is strengthened by the absorptive capacity effects of human capital in the main scenario. This result is due to the significant impact of absorbed productivity from abroad. Trade-intensive industries are not particularly skill-intensive in this economy, as Table 1 indicates. Hence, our finding for this small, open economy deviates from the skill-biased technological change demonstrated in closed economy models (Acemoglu 1998; Kiley 1999).

The expansion of the *trade-intensive* Traditional Manufacturing industry is nearly doubled when compared to the reference scenario. This result is explained by the larger absorbed productivity effect that implies that human capital now serves as an absorptive capacity catalyst. *All* private industries involved in international trade face increased absorbed productivity when compared with the reference scenario; on average, absorbed productivity increases by 2.0 per cent.

To sum up, the main scenario is characterized by productivity growth from more educated labor, domestic innovation, and absorption of knowledge spillovers from abroad. The increase in the share of high-skilled labor raises the GDP by 3.9 per cent in the long run, when growth effects have faded out. The welfare gains of 1.7 per cent, computed as the discounted value of real consumption, originate from external standing-on-shoulders effects among R&D firms, love-of-variety effects of high-tech capital among final goods industries, and external spillovers absorbed from abroad. The latter is largely obtained via the absorptive capacity effect of human capital.

3.3 Sensitivity analysis: Strengthened absorptive capacity effect of human capital

The calibrated human capital impact on absorptive capacity is largely uncertain. In the main scenario, the result of shifting the share of highly educated was partly to expand the *high-skill intensive* R&D-industry and partly to stimulate the *trade-intensive* industries. Thus, growth was partly R&D-driven and partly a result of spillovers from abroad.

The decomposition performed above by comparing the main scenario with a reference scenario serves to isolate the impact of the absorptive capacity effect of human capital. This analysis uncovered a crowding-out effect on domestic innovation. In this sensitivity analysis, we triple the initial absorptive capacity effect of human capital within the *trade-intensive* Traditional Manufacturing industry to explore the crowding-out effect further.[12]

The most striking effect is that rather than stimulating R&D, the increase in the high-skilled labor share now causes a *decrease* of 24.7 per cent in long-run patent production and of 17.7 per cent in R&D-based capital production; see Table 2. Thus, the R&D-expanding effect of increasing human capital resources is case-dependent and is not unambiguously true. Despite the 21 per cent rise in the high-skilled labor supply to the private sector, the input in the R&D industry decreases by 14.7 per cent.

Downscaled R&D has the isolated effect of reducing productivity, both through a reduced standing-on-the-shoulders effect in the R&D

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[12] In terms of eq. (6b), Ω^H is initially three times larger for a given L^H. Along the path, the difference weakens according to the diminishing absorptive capacity effects assumed. In the long run, the difference is only 10 percent.

industry and a reduced love-of-variety effect in final goods industries. In addition, lower use of high-tech capital is detrimental to the absorptive capacity of final goods industries. This effect also makes its mark on the absorbed productivity of the Traditional Manufacturing industry. In the long run, when the quantity and quality of R&D-based high-tech capital is at its lowest, as is the effectiveness shift in the absorptive capacity effect of human capital (see footnote 10), the absorbed productivity effect on the Traditional Manufacturing industry is only 2.3 per cent. However, at its maximum and along the transitional path, this effect peaks at 12.9 per cent.

High productivity within the Traditional Manufacturing industry boosts production and demand for inputs during parts of the transition. The demand for highly educated labor increases sharply, by 30.2 per cent in the long run and by more than the double in earlier periods. The education premium falls by 10.2 per cent in the long run. This is a larger fall than in the main scenario because the absorptive capacity effects of human capital are now easier to attain.

In this sensitivity scenario we are left with a technological progress entirely dominated by international spillovers. In earlier periods, progress is fast, driven by the increased human capital supply. Along the path, however, spillovers from abroad are dampened by reduced domestic R&D activity, and eventually average absorbed productivity returns to the level given in the main scenario. Long-run GDP increases less, mainly due to the fall in R&D-driven, domestic innovation. In the sensitivity scenario, the higher productivity externalities from trading during the transition results in a 0.6 percentage point larger welfare gain than in the main scenario.

4 Concluding remarks

Along with the efforts of most governments over the last couple of decades to stimulate research and development (R&D), there has been a growing concern for an apparent shortage of researchers and a relatively scarce enrollment of students with the relevant university degrees. Following a few theoretical contributions, we study the role of supply side policies to promote growth. The focus is on small, open economies in which an increased supply of highly educated workers will not only benefit growth through spurring R&D activity but is also vital for firms' capacity to absorb cross-border knowledge spillovers.

This study examines how increasing the share of highly educated labor influences domestic innovation, cross-border absorption of knowledge, and growth. The analysis is performed in a Romer-inspired endogenous growth model of a small, open economy model (Norway) that allows for spillovers through trade and absorptive capacity effects through the use of high-tech and human capital. Our model captures the realistic variety among industries with respect to factor intensities and international trade. Increasing the share of highly educated labor promotes the capacity to innovate through R&D activities alongside the capacity to absorb cross-border spillovers. If the absorptive capacity effect is sufficiently strong, education policies can even cause R&D activity to fall. Both the innovation and absorption processes contribute to higher growth and welfare.

Domestic innovation resulting from a higher share of educated labor tends to favor the high-skill (and high-tech) intensive parts of the economy. This point is recognizable from the large and closed economy models of Acemoglu (1998) and Kiley (1999). However, in this small and open economy case, productivity spillovers from abroad are stimulated and soon dominate the growth process. In the long run, industries exposed to world markets through international trading experience the highest growth while directed R&D-induced technological change plays a smaller part.

Productivity growth processes via trade raise the issue of trade promotion as a more direct alternative than education for stimulating growth for small, open economies. In a trade-reliant, developed economy, such as the Norwegian economy, however, such a strategy is only theoretical. There are hardly any import barriers left, and subsidizing export is prohibited by WTO law. Education policies could then be a second-best substitute.

Finally, we would like to highlight some features of our model that deserve a critical discussion and further examination in future research. First, in our model the increased abundance of highly educated labor, or factor intensities in general, has little impact on the direction of technological change through cross-border spillovers. Rather, trade intensity is the major determinant for its direction. If productivity spillovers were internalized, not external as in our model, the bias towards high-skilled labor would be more pronounced. Then, firms would strategically invest in absorptive capacity, and investment in human capital would intensify along with increased abundance.

Second, our model divides labor into two skill groups, and the competition for highly educated labor between innovation and absorption relies on the assumption that the resource is crucial for both processes. On the contrary, Vandenbussche et al. (2006) and Acemoglu et al (2006) model qualitatively different key resources in the two processes; innovation requires more skilled or selected resources than absorption (imitation). Their model and empirical findings indicate that labor should be divided into more than two skill groups and that this would affect the bias of technological change.

Third, this study does not address the cost side of increased education nor does it regard growth as an endogenous result of mechanisms within the educational system itself, as in models of endogenous human capital accumulation; see Eicher (1996), Redding (1996), Arnold (1998), or Grossman (2007). Including choice of education and growth effects from accumulated human capital would supplement the model and the analysis further. We leave these topics for future research.

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Appendix A. Industries

Consumer Goods and Services
Traditional Manufacturing
Polluting Transport Services
Non Polluting Transport Services
R&D industry (producing patents and high-tech capital)
Refineries
Ordinary Machinery
Building of Ships, Oil Drilling Rigs, Oil Production Platforms etc.
Construction, excl. of Oil Well Drilling
Ocean Transport, Oil and Gas Exploration, and Drilling
Dwelling Services
Power Distribution and transmission
Production of Electricity
Public Sector

Appendix B. The model structure and calibration of firm and household behavior

When firm notation *i* is suppressed, all variables in the equation apply to firm *i*. Subscripts denoting industry are also suppressed for most variables. Subscript 0, -1, or *t* denote period. When period specification is absent, all variables apply to the same period. Compared to the exposition in Section 2, we disregard inputs of intermediate goods. In consumption, *i* denotes good,*i* and *j* denotes CES composite *j*. For simplicity, other policy variables in the CGE model are disregarded.

B.1 Final goods industries

(B.1)
$$PV_0 = \int_0^\infty e^{-rt}\left(\pi_t - P_t^J J_t\right)dt = \int_0^\infty e^{-rt}\left(\pi_t - P_t^K K_t\right)dt + P_0^J K_0$$

(B.2)
$$\pi = P^H X^H + P^W X^W - wL$$

(B.3)
$$\left[\left(X^H\right)^\rho + \left(X^W\right)^\rho\right]^{1/\rho} = \left[f(L\tau, K\tau)\right]^s$$

(B.4)
$$\dot{\tau} = \dot{\tau}^* + (\lambda_1 A + \lambda_2 B)\Delta = (\lambda_0 + \lambda_1 A + \lambda_2 B)\Delta$$

(B.5)
$$A = \Omega^H \cdot \Omega^R \cdot \frac{X^W}{X},$$

(B.6)
$$B = \Omega^H \cdot \Omega^R \cdot \frac{I}{X^H}$$

(B.7a)
$$\Omega^R = \frac{\varphi\left(\dfrac{K^V / VF}{K_0^V / VF_0}\right)}{\dfrac{\varphi}{2} + \dfrac{K^V / VF}{K_0^V / VF_0}}, \qquad \Omega^{R'} > 0\ ,\ \Omega^{R''} < 0$$

(B.7b) $$\Omega^{\mathrm{H}} = \frac{\varphi \frac{\mathrm{L}^{\mathrm{H}}}{\mathrm{L}_0^{\mathrm{H}}}}{\frac{\varphi}{2} + \frac{\mathrm{L}^{\mathrm{H}}}{\mathrm{L}_0^{\mathrm{H}}}}, \qquad \Omega^{H'} > 0,\ \Omega^{H''} < 0$$

(B.8) $$C = c\left[\left(X^W\right)^{1/s} + \left(X^H\right)^{1/s}\right]$$

(B.9) $$\bar{\pi} = P^H X^H - c\left(X^H\right)^{1/s} + P^W\left(1+\alpha_2\right)X^W - c\left(X^W\right)^{1/s}$$

(B.10) $$P^H = \frac{c}{s}\left(X^H\right)^{\frac{1-s}{s}}$$

(B.11) $$P^W = \frac{c}{\left(1+\alpha_2\right)s}\left(X^W\right)^{\frac{1-s}{s}}$$

(B.12) $$s = 1/\rho$$

(B.13) $$\mathrm{w} = \left[\delta_{\mathrm{LS}}\left(\mathrm{w}_{\mathrm{LS}}\right)^{(1-\sigma_{\mathrm{L}})} + (1-\delta_{\mathrm{LS}})\left(\mathrm{w}_{\mathrm{HS}}\right)^{(1-\sigma_{\mathrm{L}})}\right]^{\frac{1}{1-\sigma_{\mathrm{L}}}}$$

(B.14) $$\mathrm{L}_{\mathrm{HS}} = \left(1-\delta_{\mathrm{LS}}\right)\left(\frac{\mathrm{w}_{\mathrm{HS}}}{\mathrm{w}}\right)^{-\sigma_{\mathrm{L}}}\mathrm{L}$$

(B.15) $$\mathrm{L}_{\mathrm{LS}} = \delta_{\mathrm{LS}}\left(\frac{\mathrm{w}_{\mathrm{LS}}}{\mathrm{w}}\right)^{-\sigma_{\mathrm{L}}}\mathrm{L}$$

(B.16) $$K = \left[\delta_{KM}\left(\frac{K^M}{\delta_{KM}}\right)^{\left((\sigma_K-1)/\sigma_K\right)} + \left(1-\delta_{KM}\right)\left(\frac{K^V}{\left(1-\delta_{KM}\right)}\right)^{\left((\sigma_K-1)/\sigma_K\right)}\right]^{\left(\sigma_K/(\sigma_K-1)\right)}$$

(B.17) $$K^V = \left[\sum_{i=1}^{R}\left(K_i^V\right)^{(\sigma_{KV}-1)/\sigma_{KV}}\right]^{\sigma_{KV}/(\sigma_{KV}-1)}$$

(B.18) $$P^{KV} = \left[\sum_{i=1}^{R}\left(P_i^{KV}\right)^{(1-\sigma_{KV})}\right]^{1/(1-\sigma_{KV})}$$

(B.19) $$J^{KM} = \dot{K}^M + \mu^{KM}K^M$$

(B.20) $$P^{KM} = (r + \mu^{KM})P^{JM} - \dot{P}^{JM}$$

$$J^{KV_i} = \dot{K}_i^V + \mu^{KV} K_i^V \tag{B.21}$$

$$P^{KV_i} = (r + \mu^{KV}) P_{K_i}^H - \dot{P}_{K_i}^H \tag{B.22}$$

B.2 R&D industry

Eq. (B.1) applies to R&D activity. In addition, the following structure describes R&D/patent production:

$$\pi = P_R X_R - wL \tag{B.2'}$$

$$X_R = [R]^{s_1}\left[f\left(L\tau, K^M\tau\right)\right]^s \tag{B.3'}$$

$$C = \frac{c}{(R)^{s_1/s}}\left[X_R\right]^{1/s} \tag{B.8'}$$

$$R = R_{-1} + X_R \tag{B.20}$$

$$\bar{\pi} = P_R(1+\beta)X_R - \frac{c}{(R)^{s_1/s}}\left(X_R\right)^{1/s} \tag{B.9'}$$

$$P_R = \frac{c}{(1+\beta)s(R)^{s_1/s}}\left(X_R\right)^{\frac{1-s}{s}} \tag{B.10'}$$

Each high-tech capital variety is delivered both to the home and export market in quantities X_{Ki}^H and X_{Ki}^W, respectively, during each period. For each variety, equations (B.2) and (B.12) apply, in addition to the following:

$$PV_{i0} = \int_0^\infty e^{-rt}\left(\pi_{it} - P_t^K K_{it}\right)dt - P_{R0} + P_0^J K_{i0} \tag{B.1''}$$

$$\left[\left(X_{Ki}^H\right)^\rho + \left(X_{Ki}^W\right)^\rho\right]^{1/\rho} = \left[f\left(L_i\tau, K_i^M\tau\right)\right]^s \tag{B.3''}$$

$$C_i = c\left[\left(X_{Ki}^W\right)^{1/s} + \left(X_{Ki}^H\right)^{1/s}\right] \tag{B.8''}$$

$$\bar{\pi}_i = P_{Ki}^H\left(X_{Ki}^H\right)X_{Ki}^H - c\cdot\left(X_{Ki}^H\right)^{1/s} + P_K^W(1+\alpha_3)X_{Ki}^W - c\cdot\left(X_{Ki}^W\right)^{1/s} \tag{B.9''}$$

(B.10") $$P_{Ki}^{H} = m_{Ki}\frac{c}{s}\left(X_{Ki}^{H}\right)^{\frac{1-s}{s}}$$

(B.23) $$\varepsilon_{Ki} = -\frac{\partial X_{Ki}^{H}}{\partial P_{Ki}^{H}}\frac{P_{Ki}^{H}}{X_{Ki}^{H}}$$

(B.24) $$m_{Ki} = \frac{\varepsilon_{Ki}}{\varepsilon_{Ki}-1} = \frac{\sigma_{KV}}{\sigma_{KV}-1}$$

(B.11") $$P_{K}^{W} = \frac{c}{(1+\alpha)s}\left(X_{Ki}^{W}\right)^{\frac{1-s}{s}}$$

(B.25) $$\left(1+\beta\right)P_{R0} = \int_{0}^{\infty} e^{-rt}\left(\overline{\pi}_{t}\right)dt$$

B.3 Consumer behavior

(B.26) $$U_{0} = \int_{0}^{\infty} u\left(d_{t}\right)e^{-\theta t}dt$$

(B.27) $$u(d_{t}) = \frac{\sigma_{d}}{\sigma_{d}-1}d^{\left(\frac{\sigma_{d}-1}{\sigma_{d}}\right)}$$

(B.28) $$W_{0} = \int_{0}^{\infty} P_{t}^{D}d_{t}e^{-rt}dt$$

(B.29) $$d_{t} = \left[\mu \cdot P_{t}^{D}\right]^{-\sigma_{d}}$$

(B.30) $$D_{t} = d_{t}(1+n)^{t}$$

(B.31) $$D_{it} = \omega_{i.0}\left(\frac{P_{jt}^{D}}{P_{it}^{D}}\right)^{\sigma_{j}}\frac{VD_{jt}}{P_{jt}^{D}}$$

(B.32) $$P_{i}^{D} = \left((1-\upsilon_{i})(P_{i}^{H})^{(1-\sigma_{HI})} + \upsilon_{i}(P_{i}^{I})^{(1-\sigma_{HI})}\right)^{\frac{1}{1-\sigma_{HI}}}$$

(B.33) $$\frac{D_{t+1}}{D_{t}} = \left(1+n\right)\left(1+g\right)$$

B.4. Variables

PV_0	The present value of the representative firm
π	Operating profit
P^J	Price index of the investment good composite
J	Gross investment
P^K	User cost index of capital composite
K	Capital composite
X^H	Output of final good firm delivered to the domestic market
X^W	Output of final good firm delivered to the export market
X	Total output of the final good firm
P^H	Domestic market price index of final good
P^W	World market price index of final good
w	Wage cost index of labor composite
L	Labor composite
L^H	High-skilled labor (subscript *0* denotes the base year value)
L^L	Low-skilled labor(subscript *0* denotes the base year value)
w^H	Wage rate high-skilled
w^L	Wage rate low-skilled
τ	Endogenous factor productivity change through absorption of international spillovers
K^V	Composite of high-tech capital
K^M	Other ordinary capital
J^{KM}	Gross investment, other ordinary capital
P^{JM}	Price of investment good, other ordinary capital
P^{KM}	User cost of capital, other ordinary capital
C	The variable cost function
c	Price index of the CES-aggregate of production factors
$\overline{\pi}$	Modified profit (the period-internal maximand of firms)

R	Accumulated number of patents/high-tech capital varieties
X_R	Production of patents
P_R	Shadow price of patents
K_i^V	high-tech capital variety *i*
P_i^{KV}	User cost of high-tech capital variety *i*
J^{KV_i}	Gross investment, high-tech capital variety *i*
P_{Ki}^H	Domestic market price index of high-tech capital variety *i*
P_K^W	World market price index of high-tech capital varieties
P^{KV}	User cost index of the high-tech capital composite
U_0	Discounted period utilities of a representative consumer
d	Consumption of a representative consumer
P^D	Consumer price index
r	Nominal interest rate
W_0	Consumer's current non-human wealth + present value of labor income + net transfers
μ	Marginal utility of wealth
D	Aggregate consumption
N	Annual population growth rate
D_i	Demand for consumer good *i*
VD_j	Aggregate expenditure on CES aggregate *j*
G	Growth rate
I	Import
P^I	Import price
P_i^D	Price of Armington composite good
A	The absorption elasticity’s export-dependent term
B	The absorption elasticity’s import-dependent term
Ω^H	The absorptive capacity from human capital

Ω^R	The absorptive capacity from R&D
$\dot{\tau}*$	Exogenous contribution to absorbed productivity growth
Δ	Productivity gap from the (exogenous) frontier
VF	Composite of variable input factors

B.5. Calibration

Model technology is calibrated to the 2002 Norwegian National Accounts.

Parameters

		Value
s	Scale elasticity	0.83
ρ	Transformation parameter between deliveries to the domestic and the foreign market	1.2
σ_K	Elasticity of substitution between variety-capital and ordinary capital	1.5
δ_{KM}	Calibrated share of other ordinary capital in the capital composite	industry-specific
σ_{KV}	Uniform elasticity of substitution applying to all pairs of capital varieties	3.0
σ_L	Elasticity of substitution between high-skilled and low-skilled labor	2.0
δ_{LS}	Calibrated share of low-skilled labor in the labor composite	Industry-specific
S_1	Elasticity of domestic spillovers	0.5
ε_{Ki}	Domestic demand elasticity for capital variety *i*	3.0
m_{Ki}	Mark-up factor for variety firm *i*	1.5
θ	Consumer's rate of time preferences	0.04
σ_d	Intertemporal elasticity of substitution	0.3
$\omega_{i.0}$	Calibrated budget share of good *i* in CES aggregate *j* in period 0	Good-specific
σ_i	Elasticity of substitution between the two consumer goods in CES aggregate *j*	0.5 for all j

σ_{HI}	Armington elasticity between imported and domestic produced varieties	4.0
ν	Initial import share in the Armington aggregate	good and user-specific
λ_0	Autonomous absorption effect	0.25
λ_1	Influence of the export term on absorption	0.05
λ_2	Influence of the import term on absorption	0.05
φ	Parameter in the Ω - functions	4.0
β	R&D subsidy	scenario-specific
α_2	General subsidy to final goods export deliveries	scenario-specific
α	Subsidy to export deliveries of high-tech capital	scenario-specific
μ^{KV}	Depreciation rate, high-tech capital	good and user-specific
μ^{KM}	Depreciation rate, other ordinary capital	good and user-specific

The elasticities of substitution in production technology range from 0.15 at the upper part of the nested tree to 0.5 at the lower part of the nested tree structure (see Figure B.1 in Appendix B) and are in the range of empirical findings (Andreassen and Bjertnæs, 2006). We have less of an empirical foundation for substitution possibilities within the composite of High-tech capital and Ordinary machinery. We assume a relatively high substitution elasticity of 1.5 while the elasticity between different high-tech capital varieties is expected to be even higher and is set to 3.0, giving a mark-up factor of 1.5 in the domestic price of high-tech capital varieties.[13]

Elasticities of scale are equal to 0.83 in all industries and fit econometric findings of moderate decreasing returns to scale in Norwegian firms (Klette 1999). The scale elasticity is at the lower end of the estimates by Klette (1999) but is chosen to avoid unrealistic industrial specialization patterns.[14] This implies that elasticities of transfor-

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[13] This result is in line with the Jones and Williams (2000) computations that exclude creative destruction (similar to our model). Numerical specifications of Romer's Cobb Douglas production functions, as in Diao et al. (1999), Lin and Russo (2002), and Steger (2005), result in far larger mark-ups. Mark-ups of 1.5 are nevertheless in the upper bound of econometric estimates (Norrbin 1993; Basu 1996). Our main motivation for staying in the upper bound area is that we model industrial R&D as outsourced to a separate industry. Thus, R&D costs are ascribed to this industry, whereas the marginal costs of final goods industries exclude this part of the costs. This finding deviates from typical regressions of mark-ups, where marginal costs include all observed costs, including industrial R&D costs.

[14] Because $\rho=1/s$, a larger elasticity of scale will imply a larger elasticity of transformation between domestic and foreign deliveries, $1/(1-\rho)$. If the elasticity of scale is close to 1

mation between domestic and foreign deliveries are equal to 4.9. Elasticities of substitution between domestic products and imported goods are assumed equal to 4. The elasticity of scale related to previous knowledge is equal to 0.5, to ensure decreasing spillover effects of the knowledge base, supported by both theoretical and empirical findings (see Jones 1995, 1999; Leahy and Neary 1999).

The labor aggregate is a CES aggregate of high-skilled (more than 4 years of university or equivalent education) and low-skilled (all others) labor. The share of high skilled labor in each industry in the base year calibration is based on calculations from Norwegian R&D statistics and Bjørnstad et al. (2002). The elasticity of substitution between high-skilled and low-skilled labor is 2. Empirical estimates range from 0.5 to 5 (Bjørnstad and Skjerpen 2006). An elasticity of substitution of 2 remains in the upper part of the estimated range.[15] The base year wage differential between high-skilled and low-skilled labor is 30 per cent, based on Bjørnstad and Skjerpen (2006). We calibrate the base year wage levels from a homogenous labor model where we assume that the wage rate is a weighted average of high-skilled and low-skilled labor in the industry. The low-skilled labor weight is 0.95.

(constant returns to scale), the elasticity of transformation will be very high, implying practically no dispersion between domestic and foreign deliveries.

[15] Sensitivity tests indicate that elasticities of substitution lower than 2 implies wage rate for high skilled that are close to and also lower than for low skilled in the first years of the simulation period. The model is also quite sensitive to changes in the supply of skilled labor.

Figure B.1. Nested structure of the production technology

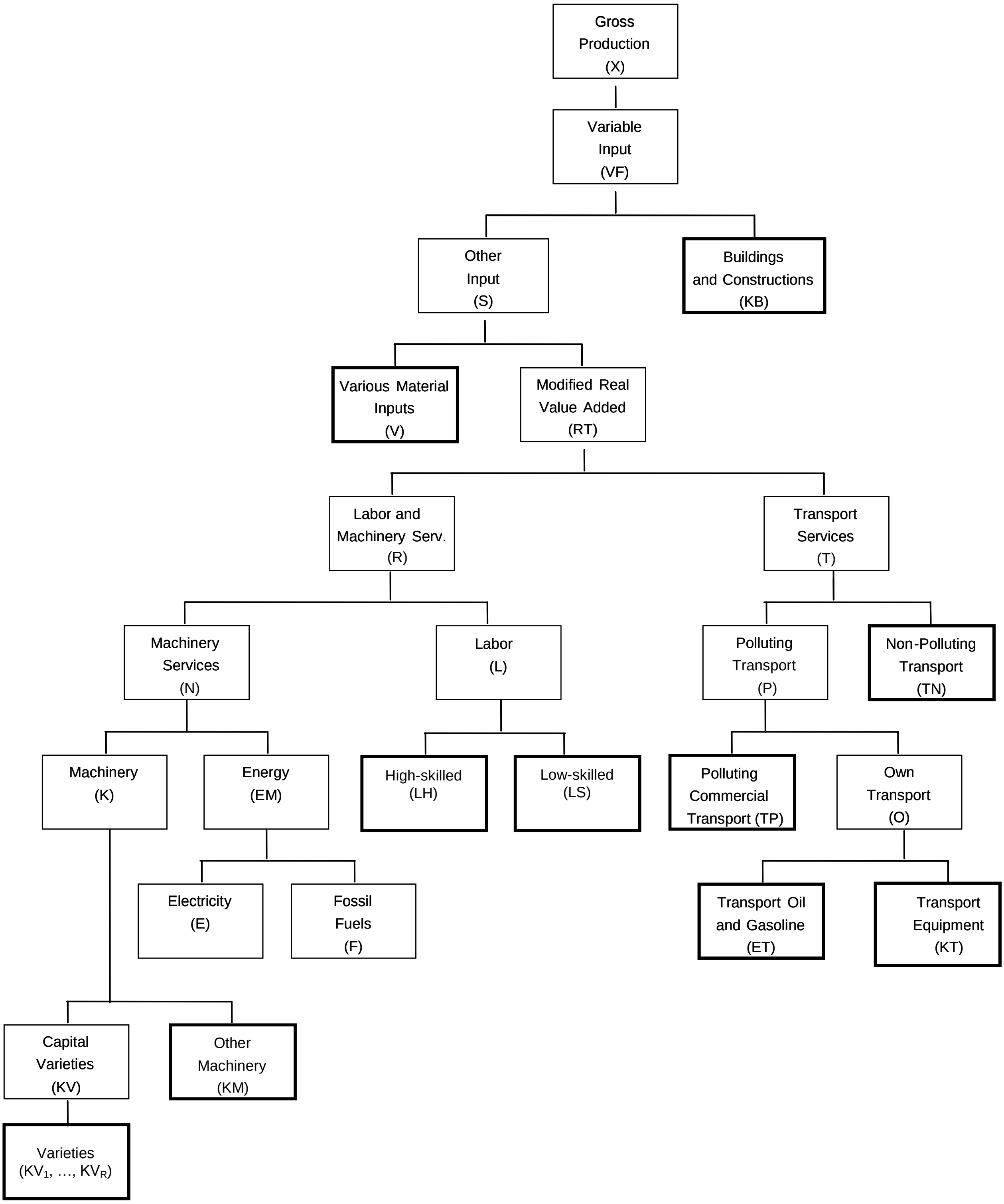
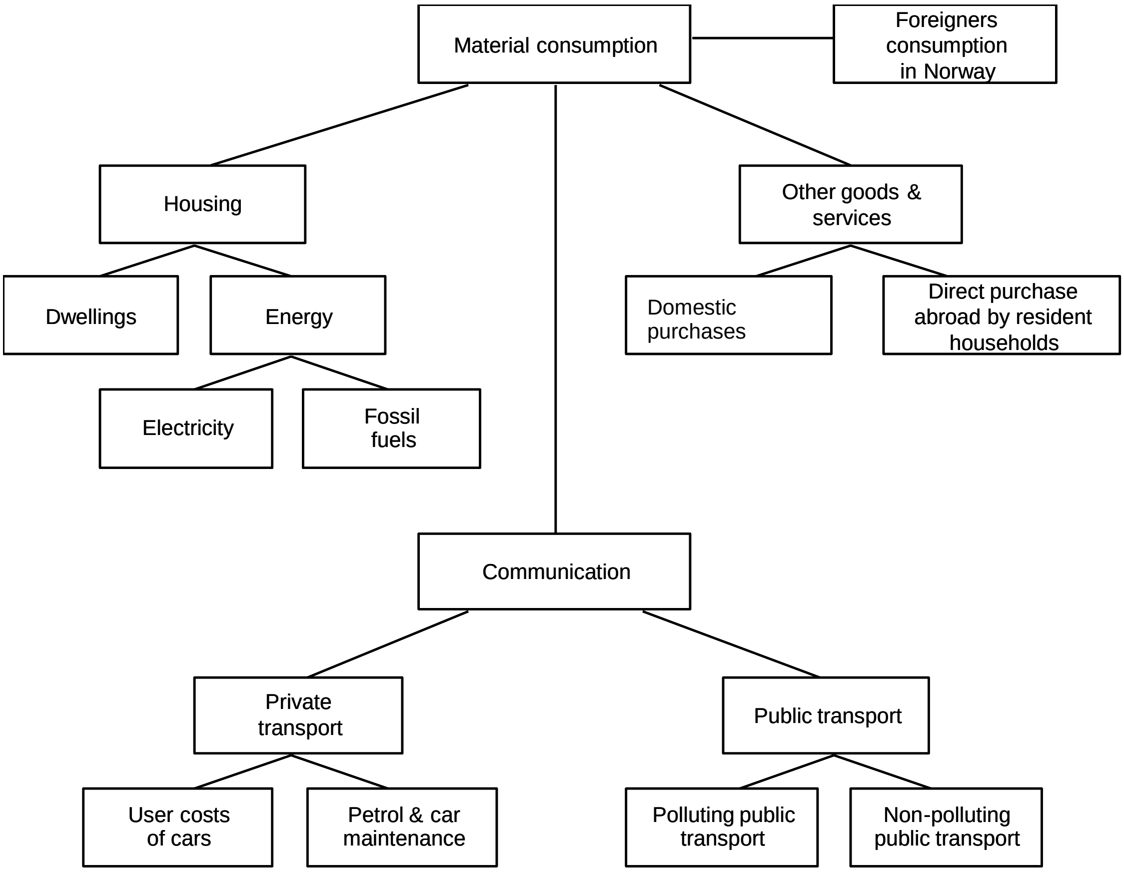


Figure B.2. The nested structure of consumption activities



Appendix C. The reference path: calibration and growth dynamics

In the transition path the exogenous growth factors are assumed to grow at constant rates. In most cases, rates are set in accordance with the average annual growth estimates in the reference scenario of Norwegian Ministry of Finance (2004) that reports the governmental economic perspectives until 2050. The population growth is set to 0.4 per cent annually. Exogenous activities, such as public consumption and output, mostly follow Norwegian Ministry of Finance (2004). The exogenous levels of offshore investments and oil and gas export result from a smoothing of their expected present values in Norwegian Ministry of Finance (2004). The smoothing is made to account for the economic significance of the Norwegian oil and gas resources without introducing another source of dynamics into the growth path.

World market prices are assumed to increase by 1.4 per cent annually. This market price increase is in the lower range of exogenous price growth estimates in Norwegian Ministry of Finance (2004) and is chosen so that exogenous inflationary impulses are more in line with internal impulses, which are dampened by the consumption smoothing features of the model. This model provides us with endogenous developments of the delivery ratios between the export and domestic markets that are more in line with those of the governmental perspectives. The international nominal interest rate is 4 per cent. The exchange rate serves as numeraire.

In Norwegian Ministry of Finance (2004) total factor productivity (TFP) growth rates are entirely exogenous and valued at, on average, 1 per cent annually. Our model distinguishes between exogenous and endogenous components and between domestic innovation and absorbed productivity/imitation engines. The exogenous productivity change is modeled in eq. (3). Its relative influence vs. the endogenous absorption factors is quantified by synthesizing available models and estimates from the econometric literature. By defining $\lambda_0 = \dot{\tau}^* / \Delta$, (3) can be expressed as $\dot{\tau} = (\lambda_0 + \lambda_1 A + \lambda_2 B)\Delta$, where λ_0 pins down the exogenous contribution, and λ_1 and λ_2 those of the import and export channels, respectively. The autonomous contribution is calibrated on the basis of Coe and Helpman (1995) but is set somewhat lower because we regard more of the productivity effects as explained (through changes in export and absorptive capacity). Estimations for

Norwegian industries of absorptive capacity effects through the import channel are found in (Grünfeld 2002). These results are fairly in line with Griffith et al. (2004) and with the historical import channel impact in Coe and Helpman (1995) when we take into account that they have not specified the influence of absorptive capacity. Export effects are found in Alvarez and Lopez (2008), Delgado et al. (2002), Baldwin and Gu (2003), and Falvey (2004). It is difficult to verify significant differences between the import and export channel, so we assume that the export and import impetuses are identical. The relative absorptive capacity effects of R&D and human capital in the main regime are based on Griffith et al. (2004), who estimate approximately similar strengths of the two factors. In the reference regime without human capital as an absorptive capacity factor, the effect of high-tech capital is calibrated stronger by adjustments in the λ_1 and λ_2-parameters (from 0.05 to 0.11).

We use the estimated 1 per cent average future TFP growth in Norwegian Ministry of Finance (2004) as a benchmark for calibrating the productivity growth in the part of the transitional reference path where a stable growth period is obtained, i.e., 60-80 years from now. In line with empirical findings, see, e.g., Coe and Helpman (1995) and Keller (2004), we calibrate 10 per cent of the domestic growth to stem from domestic innovation, while the remaining 90 per cent is driven by the growth in absorbed productivity, τ. [16] Given the rest of the parameters in the model including the scale parameters, these relative contributions form a basis for calibrating the 2002 level of accumulated knowledge, R_0 and the exogenous productivity growth at the frontier.

Some of our sources report industry-specific parameters, but we have assumed common elasticities for all. In the last part of the transition path, i.e., 60-80 years from now, the stable GDP growth rate of the reference amounts to 1.5-1.7 per cent annually, while the annual average along the path is somewhat lower, at 1.4 per cent (and in line with Norwegian Ministry of Finance, 2004). For technical reasons, we have set all exogenous and endogenous growth drivers to zero in the far future (after approximately 100 years) to ensure that a balanced growth path is reached within a limited number of periods. Sensitivity tests show that the growth rates within the stable part of the transition period appear independent of this timing; only the durability of the stable period is affected.

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[16] The domestic contribution lies in the lower bound of estimates for small, open countries, such as the Norwegian. We choose that country for this study, as several mechanisms believed to drive domestic innovations are excluded from the model, such as basic, governmental research, endogenous education, and learning by doing.