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# On general versus emission saving R&D support

**Abstract:**
We analyse welfare effects of supporting general versus emission saving technological development when carbon emissions are regulated by a carbon tax. We use a computable general equilibrium model with induced technological change (ITC). ITC is driven by two separate, economically motivated research and development (R&D) activities, one general and one emission saving specified as carbon capture and storage. We study public revenue neutral policy alternatives targeted towards general R&D and emission saving R&D. Support to general R&D is the welfare superior, independent of the level of international carbon price. However, the welfare gap between the two R&D policy alternatives is reduced if the carbon price increases.

**Keywords:** Applied general equilibrium, Endogenous growth, Research and Development, Directed technological change, Carbon policy

**JEL classification:** C68, E62, H32, O38, O41

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# 1. Introduction

In this study we ask how the R&D policy should be directed in an economy where carbon emissions are regulated by a carbon tax and R&D activities take place in development of both general and carbon emission saving technologies. A carbon tax (or tradeable carbon quotas) reduces emissions of greenhouse gases through substitution- and scale effects, and encourages development of new, emission reducing technologies. In our study the carbon tax is equal to the Pigouvian tax rate, so that the argument for subsidizing innovation activities is imperfections in the research markets that make the level of R&D-effort too low, Schneider and Goulder (1997). Such imperfections are e.g. external spillovers from previous research and development (R&D) activities and inefficiencies arising from imperfect competition in the capital variety market, Romer (1990) and Jones and Williams (2000).

In several European countries there is substantial governmental support towards development and implementation of new environmentally sound energy technologies as e.g. emission saving carbon capture and storage (CCS) and new renewable energy sources.[1] Technology policy can be a costly approach, however, if it is used as a substitute for, rather than complement, to emission reducing policy, Jaffe et al (2005). In our policy analysis we address this issue by investigating innovation policy reforms in the presence of optimal emission reducing policy. We ask two questions: *1)* What are the economic welfare effects of distributing a given amount of innovation support to development of general technologies compared to development of emission saving technologies? *2)* How will the economic welfare effects depend on the carbon tax level?

The literature on efficient policies when emission saving technological change are present, has mainly concentrated on second-best optimal carbon policy design.[2] With undersupply of investments in emission saving technology due to positive externalities in this market, the second-best optimal carbon tax is higher than the Pigouvian level, Gerlagh et al (2008). Rosendahl (2004) finds that the second-best optimal carbon taxes are largest for emission savings technology sources that give rise to the largest external spillovers (learning effects).[3] Hart (2008) models investments in both emissiong saving- and general technology with private knowledge spillovers. He finds that the second-best

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[1] As an example the Norwegian governmental support to development and implementation of CCS and environmental friendly technologies in 2009 is approximately 220 million €.

[2] Goulder and Schneider (1999) and Goulder and Mathai (2000) are early empirical approaches.

[3] In models that include investments in both emission savings and production increasing technologies, Popp (2004), Nordhaus (2002) and Gerlagh (2008) all find that the carbon tax design is influenced by endogenous technological change.

optimal carbon tax is higher than the Pigouvian level along the transitional path if the knowledge spillover in the emission saving technology is larger than in the general technology. Kverndokk and Rosendahl (2007) study time paths of subsidies to adoption of different competing technologies in a model with learning effects. They find that the subsidy should be larger to technologies that are newly adopted where the learning effects are large.

In practical policy lack of maturity is often used as an argument for additional support to R&D in new emission saving technologies. Heggedal (2008) analyses whether and how the subsidy rates should differ between R&D in emerging and mature technologies in a simplyfied semi-endogenous growth model with knowledge spillover as the only rationale for R&D subsidies. He finds that the optimal subsidy rates are unequal and that the subsidy rate to the emerging industry is higher only if the sum of the output elasticity with respect to labour and the spillover elasticity is below 1. The model lacks several important aspects that can influence the results such as imperfect competition in the market for technologies, different channels for productivity improvements from different kinds of R&D, and a price on carbon emissions that influences the underinvestment in general and emission saving R&D.

Hence, in the presence of environmental and innovation market externalities and imperfections, the relative performance of our innovation policy alternatives is not obvious. Further, other market imperfections and existing public interventions will affect outcomes. To evaluate the effects of the policies, we therefore use a newly developed computable general equilibrium (CGE) model that is calibrated to the small, open economy Norway. It includes R&D-based growth of the Romer (1990) type and imperfect competition in the markets for new technologies embodied in variety capital, Jones and Williams (2000). The model specifies two separate R&D producing processes, one producing general R&D and one producing emission savings technological solutions, specified as carbon capture and storage (CCS) solutions applicable for gas power generation.[4] Gas power production with CCS is a politically 'hot' technology in Norway receiving governmental support, and plants with full-scale carbon extraction at very high costs are close to realization. This is then an excellent example for our policy analysis. In lack of relevant empirical estimates, we have chosen identical knowledge spillover parameters in the two R&D industries.[5] In spite of the included endogenieties of growth, the dominant

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However, the results depend heavily on the specific model assumptions as fixed ratios of private to social returns of technology investments and some insufficient modelling of the R&D mechanisms.

[4] The model is documented in Bye et al. (2008).

[5] The existence of innovation externalities are well documented in the empirical literature (Griliches, 1995; Klette et al, 2000), but they differ in estimates. Popp (2006) argues that there may be large discrepancies between different R&D activities, and that the innovation externalities may be smaller in emission saving R&D than in general R&D. He provides no empirical estimates that support this presumption, though.

growth impulses are driven by external factors, in accordance with the findings for small, open countries (Coe and Helpman, 1995; Keller, 2004). [6]

Our study connects several of the separate aspects analysed in the literature into a consistent general empirical model framework and analysis. In that context we will emphasize the following properties of our model framework and analysis as contributions to the literature: Firstly, total investments in R&D are endogenous. This is in contrast to Hart (2008) where total quantity of research is exogenous. Secondly, our CGE model is calibrated to a real economy with its special characteristics; the general R&D industry is much larger than the emission savings R&D industry initially, and this influences the results of the policy analyses. Crowding out effects are important in our model framework, which is absent in e.g. Gerlagh et al (2008). The small, open economy approach allows us to model export of the domestically developed technologies as an important channel for product diffusion. National savings are separated from capital investments by the possibility of financial saving and borrowing. None of the above mentioned analyses consider the small, open economy approach with its special features regarding technological change mechanisms where most of the technological change spills over from abroad (Coe and Helpman, 1995; Keller, 2004), and uncoupled financial savings and capital investment. Thirdly, we analyse the effects of how the direction of the R&D policy will interact with the carbon tax level set by an international agreement to curb carbon emission. Fourth, we analyse policy reforms that have the same revenue effects on the public budget. This implies that we can compare the welfare effects of the different reforms, in contrast to Otto et al (2008) that have no such revenue restrictions on the policy reforms they present.

In order to explore the economic efficiency effects of directing R&D support towards emission saving R&D or towards general R&D, we study the effects reallocating a given amount of R&D support to either general R&D or to emission saving R&D. The main conclusions from our study are the following: Firstly, reallocating support to general R&D improves welfare while reallocating support to emission saving R&D reduces welfare. The productivity effect of stimulating general R&D is transmitted to the rest of the economy through increased overall productivity, while stimulating emissions savings R&D is transmitted to the rest of the economy only through a lower price of clean energy (gas power with CCS) that has a smaller effect on productivity. Reallocating R&D support from emission saving R&D to general R&D increase total R&D since the productivity of knowledge in general R&D is higher due to a relatively larger production/knowledge stock ratio. The improved

[6] Otto et al (2008) and Otto and Reilly (2008) assume that all productivity growth stems from domestic R&D. This enhances the effects of domestic R&D policy stimulation substantially.

competitiveness obtained within general variety-capital production is exploited by increased deliveries to the export markets, having a positive effect on total savings. The export effect is less prominent when R&D support is reallocated to emission savings R&D, because the increase in export deliveries of emission saving capital varieties does not outweigh the substantial fall, in absolute terms, in export deliveries of general capital varieties that occur in this policy alternative. Measured in relative terms the policy shift is much larger for the emission saving R&D industry. The effects of decreasing returns to scale combined with decreasing returns from spillovers in R&D, are both more prominent when emission saving R&D is supported. On the other hand, the simultaneous small reduction in the subsidy rate to the large general R&D industry generates a substantial reduction in general R&D in absolute terms, an effect which is enhanced by the assumption of decreasing returns in output and the knowledge spillovers. Total R&D is slightly reduced. Our simulations confirm that reallocating a given amount of R&D support from the large general R&D industry to a smaller R&D industry gives less productivity improvements.

Secondly, with a higher carbon tax the welfare gap between the two policy alternatives is reduced. The welfare gain of reallocating support to general R&D is lower, while the welfare loss of reallocating support to emission saving R&D is reduced. With a high carbon tax the demand for emission saving R&D increases. This implies that the productivity of emission saving R&D becomes higher relative to the productivity of general R&D and the value of investments in emission saving R&D increases relatively to general R&D. The effect that the productivity of emission saving R&D increases with the carbon tax level is confirmed by other studies (Greaker and Rosendahl, 2006; Heggedal and Jacobsen, 2008). Our results do, however, not contradict with the first-best result that the carbon tax should target the environmental externality and the R&D subsidy the imperfections in the research markets. Rather it states that the carbon tax influences the productivity of both general and emission savings R&D. Our analyses show that levelling a price on carbon emissions that stimulates production of carbon emission saving technologies is essential in order to obtain more welfare preferable effects of R&D support to emission saving activities.

The paper is organised as follows: Section 2 presents the main structure of the CGE model by means of a stylised exposition, while section 3 describes the empirical implementation of the model in more details together with the simulation procedures. The policy reforms are presented and discussed in section 4, while section 5 concludes.

# 2. A simplified growth model

This section presents a stylised, dynamic growth model that illustrates the main structure of the CGE model and the most important channels for transferring effects of the policies we analyse in section 4. Our empirical CGE-model includes R&D-based growth of the Romer (1990) type and specifies two separate R&D producing processes, general R&D and emission saving R&D and two corresponding capital-varieties industries. This simplified exposition presents the model structure for a representative firm in a representative industry in a given period, and for convenience firm, industry and time labels are disregarded. In this exposition we disregard all taxes, subsidies and transfers except the R&D subsidy. A uniform carbon tax representing the global carbon restriction is levied on all use of fossil fuels in production and for consumption purposes.

As in Romer (1990) the model in this simplified exposition embraces a patent producing R&D industry, a variety-capital industry, and a final goods industry. It differs from the Romer model in assuming a small, open economy, where variety-capital and final goods are traded in the world markets at exogenous prices. Domestic prices relative to world market prices determine the volumes of exports and imports. The interest rate is also exogenously given from the world market. Another feature of the small, open economy is that firm productivity is affected both by domestic growth mechanisms as in the Romer model and by exogenous technological spillovers from abroad.

We assume that all firms within each industry are small and identical. The domestic factor and product markets prices are determined by equilibrium conditions and taken as given by firms. One exception is in the domestic variety-capital market, where the firms face monopolistic competition and exhibit some market power. Labour is exogenous and perfectly mobile domestically, but immobile across borders.

## 2.1 Production of patents

The R&D industry only delivers domestically to capital variety firms that wish to buy an exclusive patent right for a new capital variety. The production of new patents in one time period, $X_R$, is given by

(1) $$X_R = R^{s_1} g(L\ , F, \tau),$$

where $g(\cdot)$ is the production function, $g'_j > 0, g''_{jj} < 0$, ($j$=$L,F$), $L$ is labour and $F$ is fossil fuels. Productivity is enhanced by endogenous domestic spillovers from the accumulated stock of knowledge embodied in patents, $R$, which are freely accessible by all incumbent and potential patent producers, so that $R = R_{-1} + X_R$. $s_1$ denotes the elasticity with respect to these spillovers. We assume decreasing returns to these knowledge spillovers, as in Jones (1995), i.e. $s_1 < 1$. The individual firms in the industry are small and do not take into account that their patent production influence productivity in future R&D, i.e. they take $R$ as given. $\tau$ denotes the factor productivity driven by external technological change, assumed to be exogenous.

In each period the maximisation problem for the firms gives the following first order condition for deliveries of patents

$$(2) \qquad P^R(1+\alpha_1) = \frac{\partial C(X_R, R)}{\partial X_R}.$$

$P^R$ is the price of patents and $\alpha_1$ is an ad valorem subsidy rate on production of patents. The cost function, $C(X_R, R)$, $C'_{X^R} > 0, C'_R < 0$, follows from the production technology in equation (1). The cost function is decreasing in $R$, i.e. positive, but diminishing spill-over effect.

## 2.2 Production of capital varieties

Each capital variety-producing firm buys one patent from the R&D industry as sunk establishment cost. Capital varieties are delivered to the final goods industry and abroad. The technology of production in each capital-variety producing firm $i$ is given by

$$(3) \qquad X\left(X_{Ki}^W, X_{Ki}^H\right) = h(L, F, \tau), \quad i = 1, \ldots, R,$$

where $h(\cdot)$ is the production function, $h'_j > 0, h''_{jj} < 0$, ($j=L,F$), $X_{Ki}^W$ and $X_{Ki}^H$ are deliveries of capital variety $i$ to the world and home market, respectively, and $X\left(X_{Ki}^W, X_{Ki}^H\right)$ is a transformation function between these deliveries, justified by different costs (e.g. transport) for deliveries to the export or domestic markets. We assume that the factor productivity effect of foreign spillovers, $\tau$, is equal for all industries. The number of capital varieties is equal to the number of patents, $R$, at each point in time.

The maximisation problem for the firms gives the following first-order conditions for deliveries to the home and export markets, respectively,

$$(4) \qquad P_{Ki}^H = m_{Ki} \frac{\partial C\left(X_{Ki}^W, X_{Ki}^H\right)}{\partial X_{Ki}^H}$$

(5) $$P_K^W = \frac{\partial C\left(X_{Ki}^W, X_{Ki}^H\right)}{\partial X_{Ki}^W}.$$

$C\left(X_{Ki}^W, X_{Ki}^H\right)$ is the cost function following from the technology of production given by equation (3). Marginal costs of deliveries to the export market equal the given world market price, $P_K^W$. In the home market, the monopoly price of capital variety $i$, $P_{Ki}^H$, is set as a mark- up, $m_{Ki}$, on marginal costs. The mark-up factor is equal for all firms.[7] This, together with the assumption of equal production and cost structure in each firm, implies that the price in the domestic market is equal for all the capital varieties, each variety is produced in equal quantities, and profits, $\overline{\pi}$, are equal for all firms.

From the persent value maximisation of the representative firm's after tax cash flow the entry condition for each capital variety-producing firm can be deduced as

(6) $$P_t^R = \int_t^\infty e^{-rz}\left(\overline{\pi}_z\right)dz.$$

$P_t^R$ is the sunk entry cost in period $t$ of buying one patent from the R&D industry. $r$ is the interest rate. In each period, firms are entering the capital variety industry until the representative firm's total discounted net profit is equal to the entry cost. The entry condition determines the price of a new patent in each period.

## 2.3 Production of final goods

The technology of production in each firm is given by

(7) $$X\left(X^W, X^H\right) = y\left(L, F, K^V, \tau\right).$$

$y(\cdot)$ is the production function, $y_j' > 0, y_{jj}'' < 0$, ($j=L,K^V,F$), $X^W$ and $X^H$ are deliveries of final goods to the world and home market, respectively, and $K^V$ represents input of the variety-capital composite.

[7] This is a usual property in these kinds of monopolistic competition models. Bye et al (2008) provides the necessary calculations.

Productivity in the final goods industry is determined by two sources. Firstly, the input of capital varieties, $K_i^V$ , is represented by so-called Spence-Dixit-Stiglitz (love-of-variety) technology of the variety-capital composite $K^V$

$$(8)\quad K^V = \left[ \int_0^R \left( K_i^v \right)^{(\sigma_{KV}-1)/\sigma_{KV}} \right]^{\sigma_{KV}/(\sigma_{KV}-1)} .$$

$\sigma_{KV}$ is the uniform elasticity of substitution applying to all pairs of capital varieties. The more varieties, i.e. larger *R*, the higher is the variety-capital productivity within the final goods industry. As in the other industries, productivity is also enhanced by the exogenously driven factor productivity change from abroad, $\tau$, which is assumed factor neutral.

## 2.4 Consumers

An infinitely lived, representative consumer maximises the intertemporal utility function

$$(9)\qquad U_0 = \int_0^\infty u(d_t) e^{-\rho t} dt , \qquad u_d^{'} > 0, u_{dd}^{''} < 0$$

given the intertemporal budget constraint

$$(10)\qquad W_0 = \int_0^\infty P_t^D d_t e^{-rt} dt .$$

*d* is total consumption for the representative consumer, $P^D$ is the price of consumption and $\rho$ is the consumer's rate of time preferences. The intertemporal budget constraint for the representative consumer sets the present value of consumption expenditure in the current and all future periods equal to total wealth $W_0$ defined as current non-human wealth plus the present value of labour income. The consumer maximisation problem gives the consumer’s consumption and saving paths.

## 2.5 Main growth mechanisms and welfare effects

Economic growth is endogenously driven by the accumulated patented knowledge stock, which improves productivity both in the R&D firms (through the dynamic knowledge spillovers) and in the final goods firms (through love-of-variety effects). Finally, parts of the factor productivity growth result from exogenous technological spillovers from abroad.

In a situation with no innovation policy, i.e. $\alpha_I = 0$, this economy is unlikely to be in a first-best state due to the market imperfections described above. The first is the dynamic knowledge spillover externality related to R&D. The second is the productivity externalities from R&D that affect productivity in final goods production through the love-of-variety characteristic of the variety-capital. These two imperfections imply that the R&D industry supplies fewer patents to the market than socially optimal. Third, the monopolistic competition taking place in the domestic variety-capital market produces a lower supply of each variety to the domestic markets than the socially efficient level. This imperfection have the opposite welfare implication as more patents crowd out intra-firm variety production and reinforce the undersupply of each variety. The net effect of these three welfare effects is, in principle, ambiguous.

Stimulating general and/or emission saving R&D directly by increasing supply of patents through a positive subsidy rate $\alpha_I$, see equation (2), increases the growth rate of this economy, because domestic productivity externalities caused by knowledge spillovers and love-of-variety are internalised.

How the innovation policy should be directed when two different R&D processes are modelled will also depend on the spillover elasticity, the channels of productivity increase from the two different kinds of R&D, the environmental externality represented by the carbon tax, other market imperfections, and existing public interventions that are present. We illustrate this by deriving the productivity or more precisely the knowledge stock's effects on R&D production that is represented by the derivative of the production function in equation (1) with respect to the knowledge stock.

$$(11)\quad \frac{\partial X_R}{\partial R} = s_1 \frac{X_R}{R} > 0$$

This productivity does not only depend on the spillover elasticity $s_I$, but also the production-knowledge stock ratio. This implies that even with identical spillover elasticisties in the two R&D industries the subsidy rates to the two R&D industries should not be equal, except when these industries are identical with respect to prices, costs and quantities. As in most real economies this is not the case in our empirical model and simulations either. In our policy simulations we analyse the welfare effects of redistributing R&D support between the two R&D industries when the baseline is characterised by equal subsidy rates.

With a higher carbon tax the demand for less carbon intensive goods increases, and especially the demand for emission saving R&D. Higher production of R&D (represented by the marginal productivity of labour $g_L^{'}$) has positive impact on the productivity, illustrated by

(12) $$\frac{\partial^2 X_R}{\partial R \partial L} = s_1 R^{(s_1-1)} g_L' > 0 .$$

Even if there is decreasing returns to knowledge accumulation, increased production of R&D (for a given knowledge stock), has a positive effect on the knowledge stock's effect on production. With a higher carbon tax the increase in emission saving R&D and the corresponding effect on productivity can be larger than for general R&D.

# 3. The empirical CGE model

This section describes the main refinements of the numerical model compared to the stylised description, and how it is quantified in order to fit the Norwegian economy. Bye et al. (2008) is a complete model documentation.[8] The model has a detailed industry structure with two R&D industries, general and emission saving, two variety-capital industries, general and emission saving, and 16 final goods industries[9] (one public, 15 private; see table A.1 in appendix A for a list). The final goods industries also deliver goods to each other according to the empirical input-output structure. Transfers, tax and subsidy wedges are represented in detail. Imports are modelled as imperfect substitutes for domestically produced goods (Armington function), while export deliveries are imperfect substitutes for home market deliveries (constant-elasticity-of-transformation (CET) technology). Financial savings are endogenously determined, subject to a non-ponzi game restriction that prevents foreign net wealth from exploding in the really long run. The exchange rate serves as numeraire.

## 3.1 Industries

***Final goods industries exclusive of electricity***

The behaviour of the final goods industries is described in section 2.3. The technology of production is given by constant elasticity of substitution (CES) functions. The entire nested input factor tree of CES aggregates, with a detailed description of the use of fossil fuels for production and processing purposes and for transport, is presented in figure B.1, Appendix B. Productivity changes in the final goods industries come from two sources, one foreign and one domestic. The exogenously driven factor-productivity change from abroad, which represents the adoption of international technological change, is assumed to be neutral across factors and industries and to increase the efficient input of each factor.

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[8] The main model equations and parameter values are presented in appendix B.

The domestic source of productivity change for the final goods industries exclusive of electricity is the *general* capital varieties used in production, generating the love-of-variety effect, as presented in more details in section 2.3.

***The electricity industries***

Electricity is generated in three different production processes (industries) and distributed by a fourth. The three generation processes are based on hydropower, gas power without CCS, and gas power with CCS, respectively. Hydropower production is exogenous and the production technology is described by the same nested CES structure as for the other final goods. The CES structure of input factor use in the gas power industries differs from other industries in that gas and gas transport are additional inputs (figure B.2, Appendix B). Both gas power industries use capital varieties. There is, however, an important difference. While gas power firms without CCS invest in *general* capital varieties also used in other final goods industries (including the hydropower industry), the gas power industry with CCS uses only *emission saving* capital varieties.

The behaviour of the two gas power industries is based on standard profit maximization as for the other final goods industries. In order to avoid zero production in one of these industries as the costs of production are not equal, we assume that gas power with and without CCS are close, but not perfect substitutes. We model the total production of gas power as a CES composite of gas power with and without CCS (see figure B.3 in Appendix B). The domestic market price for electricity is equal to the composite price of gas power following from the production costs in the gas power industries. Since the unit cost of production in hydropower is relatively low this industry earns high profits, interpreted as a natural resource rent. The generated electricity is purchased by a distribution industry. The output level in this industry is set according to the available amount of electricity. It charges distribution and transmission costs, which are passed on to the users. These may vary among demanders. Export and import activities are also handled by the distribution industry. To simplify the model solution we assume exogenous net import of electricity.

***The R&D industries***

There are two R&D industries, *general* and *emission saving*. The emission saving technology in this study is exemplified by gas power production with CCS. This technology enables power production with low carbon emissions. The general R&D industry delivers new patents to domestic firms that

[9] The following industries are treated exogenously: the governmental sector, the offshore production of oil, gas, and pipeline transport, and ocean transport.

wish to enter the industry producing general capital varieties, while the emission saving R&D industry delivers new patents to domestic firms that wish to enter the industry producing emission saving (CCS) capital varieties. The modeling of the two R&D industries is identical. The firms in the R&D industries have the same nested CES production technology as the final goods industries, except that the R&D industries do not use the differentiated capital varieties.[10] There are no spillovers in knowledge between general and emission saving R&D.[11]

***The variety-capital industries***

As for the R&D industries, there are two industries producing variety-capital, *general* and *emission saving*. The general variety-capital industry delivers variety-capital to all final goods industries except the gas power industry with CCS. The emission saving variety-capital industry delivers only to the gas power industry with CCS. As for the R&D industries, we exclude variety-capital as a production factor. The modeling of the two variety-capital industries is identical.

## 3.2 Consumer behavior

The intertemporal utility maximisation determines the consumer's consumption-savings path. We use a CRRA (Constant Relative Risk Aversion) intertemporal utility function[12]. We assume that the consumer's rate of time preference equals the nominal interest rate for the entire time path. The consumer's choice of total consumption in each period is allocated across 10 different goods and services according to a nested CES structure. The structure is given in Figure B.4, Appendix B.

## 3.3 Emissions

Emissions of greenhouse gases (GHGs)[13] are based on factor inputs to consumer activities and production in all industries. The use of factor inputs is converted into emissions according to activity- and industry-specific technical parameters (Bye et al., 2008). Emissions are converted into $CO_2$ equivalents, and a uniform tax is imposed on them. This carbon tax can be seen as either a direct tax or a quota price in a well functioning market. Either way, the tax can be thought of as representing the marginal costs of emissions for the economy, where the costs result from an international agreement of

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[10] This choice is made to avoid cumulative multipliers of the love-of-variety effect.

[11] This choice is made to be able to identify the different productivity channels.

[12] CRRA utility function, $U_0 = \sum_{t=0}^{\infty} \frac{1}{(1+\theta)^t} \frac{\sigma_d}{\sigma_d - 1} d_t^{\left(\frac{\sigma_d - 1}{\sigma_d}\right)}$, $\sigma_d$ is the intertemporal elasticity of substitution.

[13] The GHGs included in the model are: carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons.

curbing carbon emissions. The environmental impacts of emissions are not included in the model and there are no feedback effects.

## 3.4 Equilibrium conditions

The model is characterized by equilibrium in each period in all product markets and the labor market. It also incorporates a detailed account of the revenues and expenditures of the government. The government produces services and purchases intermediates from the industries and abroad. Changes in government budgets are neutralized by lump-sum transfers in each period.

Intertemporal equilibrium requires fulfillment of two transversality conditions: the limits of the total discounted values of net foreign debt and real capital must both be zero. The model is characterized by a path-dependent balanced growth path solution (or steady-state solution). This implies that both the transitional path and the long-run stationary solution differ between simulated scenarios. To ensure a long-run balanced growth path the rate of technological change for each input factor in each industry must converge to the same rate and this rate must equal the growth rate in per capita consumption.[14] Section 3.6 gives more details on how the balanced growth path is achieved.

## 3.5 Data and parameters

The model is calibrated to the 2002 Norwegian National Accounts (NA). The elasticity of substitution between the different capital varieties is assumed to be 5.0 for both general and emission saving variety-capital, giving a markup factor of 1.25 for the domestic price of both general and emission saving variety-capital.[15] The elaticities of scale are equal to 0.83 in all industries and this is at the lower end of econometric findings of decreasing returns to scale in Norwegian firms (Klette, 1999). The elasticity of scale related to previous knowledge is equal to 0.4 in both the general and emission saving patent industries, in order to ensure decreasing spillover effects of the knowledge base, supported by both theoretical and empirical findings (see Jones, 1995 and 1999; Jones and Williams, 2000). Appendix B.6 gives an overview of elasticities of substitution and other parameter values.

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[14] The population growth rate must also be constant.

[15] This is in line with the Jones and Williams (2000) computations, which exclude creative destruction, similar to our model. Numerical specifications of Romer's Cobb–Douglas production functions, as in Diao et al. (1999) and Lin and Russo (2002), result in far larger markups. Markup factors of 1.25 are nevertheless in the upper bound of econometric estimates (Norrbin, 1993; Basu, 1996). Our motivation for staying in the upper bound area is the fact that the capital varieties represent a small share of machinery capital and, thus, of total inputs. This, in isolation, drives up the markups required to calibrate the model.

The emission coefficients assigned to factor inputs, production processes and consumer activities are calibrated by data from the NA and corresponding Emission Accounts. Total Norwegian emissions of GHGs in 2002 are 56.1 million tonnes of $CO_2$ equivalents.

In 2008, there is one gas power plant in operation and one under construction in the Norwegian economy.[16] Several other plants are planned. At present, none of these plants incorporates CCS technology. However, the plants have timetables for implementation of full-scale extraction of $CO_2$ [17]. To roughly reflect the Norwegian situation, the model is calibrated to include two 860 megawatt gas power plants, one with CCS and one without CCS. Production costs of gas power are based on Statoil (2005).[18] Basically, capital and operating costs are doubled for a CCS plant compared with a non-CCS plant, and the required gas input is about 20 percent larger for a CCS plant. Appendix C gives more information on costs and prices in the gas power industry. The emission saving R&D production is quite low in the base year, 30 million €, in line with the information obtained from the Norwegian Research Council.

## 3.6 Baseline scenario and balanced growth

Along the *baseline scenario*, the exogenous growth factors are assumed to grow at a constant rate. In most cases, rates are set in accordance with the average annual growth estimates in the baseline scenario of Norwegian Ministry of Finance (2004), which reports the government's economic predictions until 2050. In the government's evaluation, total factor productivity growth is entirely exogenous and valued at, on average, 1.0 percent annually. Our model distinguishes between exogenous and endogenous factor productivity components. In line with empirical findings (e.g. Coe and Helpman, 1995; Keller, 2004), we ascribe 90 percent of domestic total factor productivity growth to the exogenous diffusion of international technological change; the remaining 10 percent is the result of domestic R&D.[19] The latter forms a basis for calibrating the 2002 level of knowledge[20] and the remaining parameters of the model. The international nominal interest rate is 4 percent. All policy variables are constant in real terms at their 2002 levels.

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[16] The plant in operation is at the Kårstø power plant; the one under construction is at Mongstad. In addition, gas power is used in specific industries offshore and for processing purposes in certain industries. In the model, this power production is not separated from the user industries.

[17] CCS technology is planned to be operational by 2011 at Kårstø and 2014 at Mongstad.

[18] Statoil (2005) bases costs on combined-cycle power plants with amine-based post-combustion separation of $CO_2$. Reduced energy efficiency, pipeline transport, and storage in geographic formations are included in the costs.

[19] Ten percent from domestic R&D is in the lower bound of estimates for small, open countries like Norway. We have chosen this lower-bound estimate because several mechanisms believed to drive domestic innovations are excluded from the model, like basic government research, endogenous education, learning-by-doing, and direct absorptive capacity related to R&D.

[20] The emission saving knowledge stock is calibrated to grow at the same rate as the general knowledge stock when the two gas power industries demand equal amounts of capital varieties. Since both knowledge stocks are indexed to unity in the base

We have implemented the current (2007) Norwegian support to R&D activities in private industries. This amounts to an R&D support of approximately 233 million €, or a 6.46 per cent subsidy rate. We assume this rate to continue to be offered to both general and emission saving R&D activities along the baseline scenario.

In the long run, i.e. 60–70 years from now, the economy reaches stationary growth rates. The GDP grows by 1.5 percent annually; consumption grows 0.5 percentage points lower, as net exports are increasing more in this period. The 10 percent contribution from the endogenous productivity impact of domestic innovations requires a relatively strong growth in both general and emission saving R&D production and the generation of the two kinds of new variety-capital: they all grow about 3 per cent annually.[21]

The constant, uniform carbon tax in the baseline replaces a variety of taxes on GHGs in the Norwegian economy. It is set at about 11 € per tonne of $CO_2$ equivalents to replicate baseline emissions in 2002 of 56.1 million tonnes of $CO_2$ equivalents. Emissions rise substantially through the period to 92.0 million tonnes in 2050 and 120.5 million tonnes in 2070 both due to general economic growth and the increased supply of electricity produced by gas power without CCS.[22] About 16 percent of the increase in emissions comes from the gas power industry.

# 4. Effects of directed R&D policies

## 4.1 The policy shifts

We compare two different policy shifts in order to explore the economic efficiency effects of directing R&D support towards emission saving R&D or towards general R&D. Our two policy shifts use the baseline scenario described in section 3.6 as the benchmark. In the first policy shift, the *general R&D support scenario*, we reallocate a given amount of the R&D support from emission saving R&D to general R&D. In the second policy shift, the *emission saving R&D support scenario*, we reallocate the same amount of the R&D support from general R&D to emission saving R&D.

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year, this means that an equal growth in the knowledge stocks gives the same productivity increase in the use of general and emission saving capital varieties. Bye et al. (2008) gives more details of the modelling and calibration procedures.

[21] Eventually, in the distant future (after about 90 years), all exogenous and endogenous growth mechanisms are cut off. This is technically motivated, in order to ensure that the economy eventually reaches a balanced growth path (steady state) and that this growth path satisfies the transversality conditions described in Section 3.4. The relative effects of the different policy analyses are independent of this assumption.

[22] The power-intensive industry (production of metals etc.) is assumed to have limited growth possibilities in the BAU path due to restrictions on the supply of cheap hydro power for the production process.

We assume that global carbon emissions are regulated by international commitments on carbon regulations in each country, and an international market for carbon quotas generates a global price on carbon emissions. The quota price is equal to a global carbon tax in an efficient market. Domestic producers and consumers can sell or purchase carbon quotas in the international quota market at the given world market price of carbon emissions.

The policy shifts are implemented in the first year of simulation (2002) and kept constant throughout the whole simulation period. We report the long-run effects 70 years from now, when the economy has obtained stable growth rates. The effects of the policy alternatives, measured as per cent deviations from the baseline scenario, are given in Table 1.

**Table 1. Long run effects of the R&D policy shifts. Per cent changes from the baseline scenario.**

| *Carbon tax* | 11 € | | 75 € | |
|---|---|---|---|---|
| *R&D policy shifts* | General | Emission saving | General | Emission saving |
| *Subsidy rate (change, per cent point rate):* | | | | |
| *General R&D* | 0.05 | -0.04 | 0.04 | -0.04 |
| *Emission saving R&D* | -6.46 | 4.31 | -5.12 | 3.15 |
| *The R&D industries, production:* | | | | |
| *Total R&D* | 0.13 | -0.05 | 0.00 | 0.07 |
| *General R&D* | 0.40 | -0.41 | 0.45 | -0.47 |
| *Emission saving R&D* | -44.38 | 57.71 | -41.70 | 51.03 |
| *The variety-capital industries, production:* | | | | |
| *General R&D based capital* | 0.18 | -0.18 | 0.19 | -0.19 |
| *Emission saving R&D based capital* | -20.64 | 20.80 | -20.27 | 19.71 |
| *The R&D industries, prices:* | | | | |
| *General R&D* | -0.05 | 0.05 | -0.05 | 0.04 |
| *Emission saving R&D* | 5.68 | -3.61 | 4.65 | -2.93 |
| *The variety-capital industries, prices:* | | | | |
| *General R&D based capital* | -0.01 | 0.01 | -0.02 | 0.02 |
| *Emission saving R&D based captital* | 1.57 | -0.92 | 0.88 | -0.45 |
| *Electricity industries, production:* | | | | |
| *Total* | -0.45 | 0.38 | -2.15 | 1.75 |
| *Gas power without CCS* | 0.81 | -0.69 | 3.13 | -2.52 |
| *Gas power with CCS* | -3.69 | 3.14 | -2.76 | 2.25 |
| *Power intensive industry, production* | -0.06 | 0.05 | -0.14 | 0.11 |
| *Electricity price* | 0.19 | -0.17 | 0.45 | -0.37 |
| *Welfare* | 0.003 | -0.003 | 0.0016 | -0.0026 |

#### *4.1.1 General R&D support*

We first consider the effects of reallocating a given amount (equal to 2.3 million €) of the R&D support from emission saving R&D to general R&D. This implies that all subsidies are removed from the emission saving R&D and transferred to general R&D, increasing its subsidy rate with 0.04 per centage points. The subsidy-increase shifts the marginal costs of general R&D production downwards and the price of general R&D falls. More firms enter the general variety-capital industry, and both production by each firm and the individual firm's profit fall. In addition, the positive spillover effect from the accumulated stock of general R&D shifts the marginal cost curve further downwards and reinforces the partial market dynamics. This spillover mechanism is perpetual but exhaustive, and general R&D increases by 0.4 per cent in the long run.

As the number of general capital varieties increases, both the mark-up price and the domestic production of each variety are reduced. The productivity of general variety-capital increases with the number of varieties because of love of variety in the final goods industries. This, combined with lower price on each capital variety increases the demand for general capital varieties. Improved competitiveness obtained by stimulating general R&D are exploited by increased export deliveries of general capital varieties that increases slightly more than corresponding deliveries for the home market.

The results are also influenced by indirect changes in all factor markets. Subsidising general R&D production increases the demand for other inputs, like labour, intermediates including electricity, and other investment goods in the general R&D- and variety-capital industries. For most other industries the unit costs of production increase, and export and home market deliveries fall, both in the short and long run. This implies that in most activities the productivity effect from increased general R&D is not large enough to outweigh the cost-increases on intermediates.

For the emission saving R&D industry the picture is the opposite. Removing the R&D subsidy induces a fall in emission saving R&D of 44.4 percent, while the production of emission saving variety-capital falls by 20.6 per cent. Emission saving R&D is relatively small compared to general R&D in the baseline scenario, and the large fall does not outweigh the increase in general R&D; total R&D increases by 0.13 per cent. The large reduction in the number of new patents in the emission saving R&D industry implies less positive knowledge spillovers in this industry. Increased input costs also contribute to the upward shift in the cost curve and the price of emission saving patents increases by 5.7 per cent.

In the capital intensive production of gas power without CCS, the productivity enhancement from increased general R&D lowers the production costs, and gas power without CCS becomes relatively cheaper than gas power with CCS. Gas power with CCS also experiences a productivity loss due to the withdrawel of the subsidy to emission saving R&D. As a result, production of electricity is reallocated towards gas power without CCS. However, gas power without CCS is still more costly than gas power with CCS, and the electricity price increases, while total production of electricity falls.

The effects on welfare, measured as total discounted utility, are positive. As pointed to in section 2.5, equal subsidy rates are generally not recommended. The main contributions to the welfare gain originate from increased general R&D and general variety-capital production which generates positive knowledge spillover in production of general R&D, and the positive love-of-variety effect in the demand for general variety-capital. These are counteracted by the welfare loss of downscaling production within each monopoly firm producing general capital varieties. The opposite effects are present for the emission saving R&D and variety-capital production following the removal of the R&D subsidy. The fall in emission saving R&D is considerable and this has a large negative effect on the productivity of gas power with CCS. However, the fall in emission saving R&D is not large enough to outweigh the increase in general R&D. In the presence of various distortions in the economy, other reallocations may also affect efficiency and welfare. One additional positive contribution to welfare stems from the fact that savings increase. As opposed to closed economy models, national savings are separated from capital investments by the possibility of saving and borrowing abroad. Investments in real capital are reallocated to investments in financial capital. The accumulation of net foreign wealth, especially due to increased competitiveness and export of general capital varieties along the simulation path, outweighs the reduction in real capital accumulation and savings increase. Capital income taxation drives a wedge between private and social returns to capital, and savings are too low from an intertemporal efficiency point of view. Increased savings reduce this inefficiency, and consumption is slightly higher along the path.

#### *4.1.2 Emission saving R&D support*

We now consider the effects of reallocating R&D support from general R&D to emission saving R&D. Compared to the general R&D support alternative in section 4.1.1, stimulating emission saving R&D by additional 2.3 million € in each year is a substantial support relative to the industry's initial size. The calculated increase in the subsidy rate is 4.3 per centage points while the subsidy to the general R&D industry is only slightly reduced.

The subsidy-increase to emission saving R&D initiates the same mechanisms in the emission saving R&D industry as did more support to general R&D in the general R&D industry. Long run emission saving R&D is 57.7 per cent higher than in the baseline scenario, while the production of emission saving variety-capital is 20.8 per cent higher. The patent price and the price of the emission saving capital composite are both reduced (-3.6 per cent and -0.9 per cent, respectively) and this lowers the cost of producing gas power with CCS. More R&D in emission saving CCS technologies enhances the productivity of gas power production with CCS, and production of electricity is reallocated towards gas power with CCS.

Directing the R&D support towards emission saving R&D has a negative effect on welfare. The policy shift is much larger for the emission saving R&D industry measured in relative terms, while the effects in absolute terms are smaller. The effects of decreasing returns to scale combined with decreasing returns from the spillovers in R&D, are both more prominent in the emission saving R&D support case. Putting the other way around, the small reduction in the subsidy rate to the large general R&D industry generates a substantial reduction in general R&D in absolute terms, and total R&D is slightly reduced. As decreasing returns to scale reduces the positive effects of higher R&D subsidy to emission saving R&D, it enhances the reduction for the general R&D industry. Lower general R&D has a negative effect on general capital productivity. Our simulations confirm that reallocating a given amount of R&D support to from a large general R&D industry to a small R&D industry gives less productivity improvements. The productivity effects of stimulating emission saving R&D are transmitted to the rest of the economy through a lower price of electricity. A lower electricity price is especially beneficial for the *power intensive industry*, and production in this industry increases. The reallocations of resources to the *power intensive industry,* contribute negatively to welfare since this industry initially faces several favourable policies.[23] The positive effects of higher export of power intensive goods and emission saving capital varieties are outweighed by the fall in export of general capital varieties, and total export is reduced. Savings are reallocated from financial to real capital, and consumption is lower along the transitional path. Net foreign wealth and total savings are reduced, contributing negatively to welfare.

## 4.2 Global carbon restrictions and directed R&D support

We investigate how the economic welfare effects of directed R&D support depend on the level of the global carbon restriction imposed by the carbon tax. The carbon tax influences the markets for energy commodities and abatement capital, and interacts with the innovation markets imperfections. We perform a new *high carbon tax baseline scenario* with a global carbon quota price of 75€ per tonnes

[23] The favourable policies include lower electricity prices and lower payroll tax rates.

$CO_2$-emissions. The high carbon tax is implemented in the first year of simulation and kept constant at the same real level for the whole simulation period. The *high carbon tax baseline scenario* is made public revenue neutral by lump sum transfers to the consumers. The same R&D policy alternatives as described in section 4.1 are then performed on this high carbon tax baseline scenario. [24] The simulation results are given in Table 1 and the welfare effects of the R&D policy alternatives for the two different carbon tax levels are shown in Figure 1.[25]

With a high carbon tax, the demand for both kinds of technological improvements increases and the effect is strongest for emission saving R&D. Resources are reallocated to R&D activities and both kinds of R&D increases. Another effect is that with a high carbon tax production of gas power with CCS crowds out production of gas power without CCS, and along the high carbon tax baseline scenario electricity is predominantly produced by gas power with CCS. Even though the R&D activities increase, GDP and welfare are slightly lower than in the baseline scenario with the low carbon tax. This reflects the contractionary effects on ordinary production and consumption of the high carbon tax.

With a high carbon tax the *welfare gain* of the general R&D subsidy alternative is lower and the *welfare loss* of the emission saving R&D subsidy alternative is reduced compared to the low carbon tax alternative. For *the general R&D support alternative* the main explanations are: Firstly, the reduction in emission saving R&D from the withdrawal of subsidies nearly outweighs the increase in general R&D. This is in contrast to the significant increase in total R&D in the low carbon tax alternative. Secondly, since electricity is mainly produced by gas power with CCS in the high carbon tax baseline scenario, the electricity market is more sensitive to cost increases for gas power with CCS. This enhances the effects of the reduced subsidy rate to emission saving R&D. Energy costs increase substantially, having a negative effect on production and consumption. This is especially prominent for exporters that are price takers in the world markets. Thirdly, reallocation of savings to housing capital[26] and lower total savings (real and financial capital) both contribute to lower welfare. The effects that contribute to lower welfare gain in the general R&D support case with the high carbon tax are the same effects that contribute, with an opposite sign, to a smaller welfare loss in *the emission saving*

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[24] The same amount of R&D support, 233 million € (measured as an annuity) is distributed on the two R&D industries as in the low carbon tax baseline scenario. The calculated marginal subsidy rate that corresponds to this amount of total R&D support is 6.1 per cent, slightly lower than in the low carbon tax baseline scenario. This is due to increased activity in the R&D industries in the high carbon tax baseline scenario.

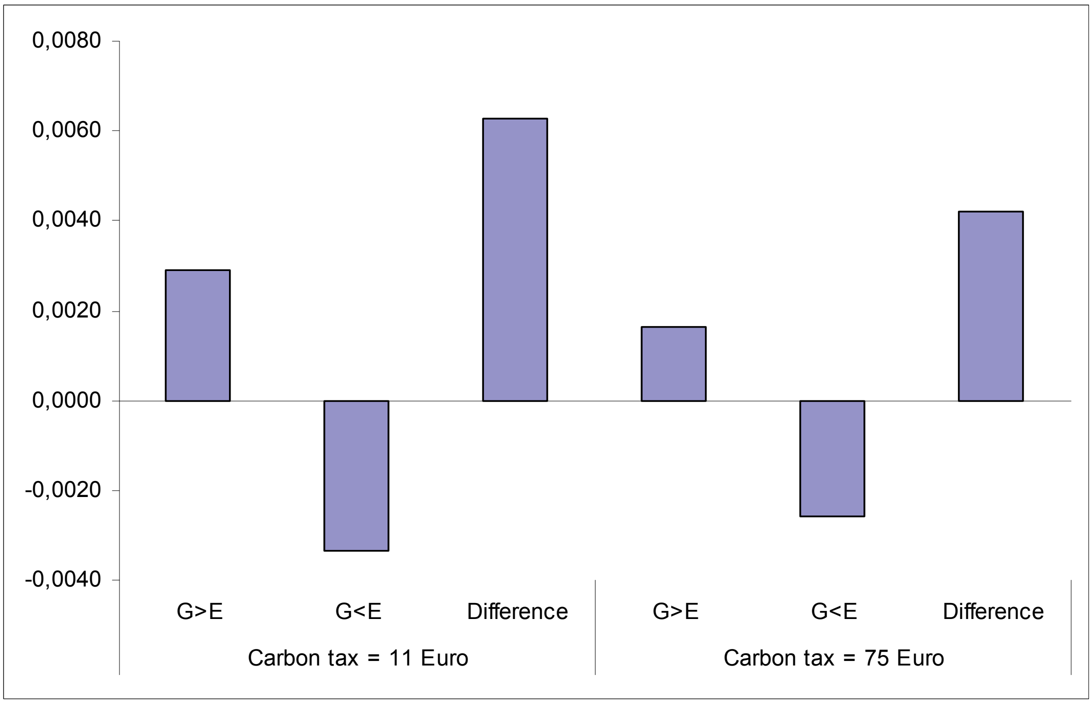
[25] In the high carbon tax baseline scenario emission saving R&D is higher than in the low carbon tax scenario. Due to higher production the revenue neutral change in the subsidy rate (per cent points) to emission saving R&D is lower. The effects of the R&D policies, measured as per centage changes from the high carbon tax baseline scenario are then smaller for emission saving R&D in both innovation policy alternatives.

[26] Housing is lenient taxed initially.

*R&D support case* with the high carbon tax, compared to the low carbon tax alternative.[27] Emission saving R&D increases and outweighs the fall in general R&D and total R&D increases. Higher productivity in gas power with CCS results in cost reductions, lower electricity price and a substantial increase in production of electricity. Lower electricity price contributes to dampen the negative effects on costs of lower productivity in all other industries following the reduced subsidy rate to general R&D. Export deliveries of traditional goods and ordinary capital increase slightly in this alternative. Saving is reallocated from real to financial capital and the effect on total savings is less negative compared to the case with low carbon tax.

Even if the discrepancy in welfare effects are reduced (Figure 1) it is still welfare superior to support general R&D compared to emission saving R&D. Our analyses also show that levelling a price on carbon emissions that stimulates production of carbon emission saving technologies (gas power with CCS), is essential in order to obtain more welfare preferable effects of R&D support to emission saving activities. Sensistivity analyses indicate that the carbon tax must be very high in order to make the emission saving R&D support case welfare superior to the general R&D support case.

**Figure 1.** Welfare effects of R&D policy shifts, percentage change from respective baseline scenarios




G = General R&D support, E = Emission saving R&D support
Difference = Welfare effect G – Welfare effect E

# 5. Concluding remarks

In this study we ask how the R&D policy should be directed in an economy where carbon emissions are regulated by a carbon tax and R&D activities take place in development of both general and carbon emission saving technologies. In our study the carbon tax is equal to the Pigouvian tax rate, so that the argument for subsidising innovation activities is imperfections in the research markets that make the level of R&D-effort too low. Such imperfections are external spillovers from previous research and development (R&D) activities and inefficiencies arising from imperfect competition in the capital variety market.

In our policy analysis we ask two questions: *1)* What are the economic welfare effects of distributing a given amount of innovation support to development of general technologies compared to development of emission saving technologies? *2)* How will the economic welfare effects depend on the carbon tax level?

The main conclusions from our study can be summarised as follows: Firstly, reallocating support to general R&D improves welfare while reallocating support to emission saving R&D reduces welfare. The productivity effect of stimulating general R&D is transmitted to the rest of the economy through increased overall productivity, while stimulating emissions savings R&D is transmitted to the rest of the economy only through a lower price of clean energy (gas power with CCS), having a smaller effect on producitivity. Reallocating R&D support from emission saving R&D to general R&D increase total R&D, and the improved competitiveness obtained within general variety-capital production is exploited by increased deliveries to the export markets. This export effect is less prominent when R&D support is reallocated to emission savings R&D, because the increase in export deliveries of emission saving capital varieties does not outweigh the substantial fall, in absolute terms, in export deliveries of general capital varieties that occur in this policy alternative. In the case of decreasing returns to scale and knowledge spillover, our simulations confirm that reallocating a given amount of R&D support from a large general R&D industry to a small R&D industry gives less productivity improvements.

Secondly, with a higher carbon tax the welfare gap between the two policy alternatives is reduced. With a high carbon tax the demand for emission saving R&D increases. This implies that the productivity of emission saving R&D becomes higher relative to the productivity of general R&D and the value of investments in emission saving R&D increases relatively to general R&D. Our results do, however, not contradict with the first-best result that the carbon tax should target the environmental externality and the R&D subsidy the imperfections in the research markets Rather it states that the carbon tax influences the productivity of both general and emission savings R&D.

Our results show that it is essential to level a price on carbon emissions in order to stimulate the demand for emission saving R&D. In addition, even with identical spillover parameters for the two kinds of R&D, it is welfare superior to reallocate R&D support from emission saving R&D to general R&D. The reason for this is that the relative size of the industry matters, combined with different transmission channels for the productivity effects to the rest of the economy. The emission saving R&D industry is small compared to general R&D, but being small is not an argument for obtaining large subsidies. The repeatedly pressure from different politicians and environmental interest groups to support emission savings R&D relatively more than general R&D, may only be justified if the output and spillover parameters are significantly larger for emission saving R&D. It is left for future research to investigate whether there are sufficiently large differences in these parameters in emission saving R&D compared to general R&D.

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## Appendix A

**Table A.1: Production sectors in the model**

| ITC Code | Production Sectors |
|---|---|
| 20 | Other commodities and services |
| 30 | Power-intensive industry |
| 32 | Polluting transport |
| 33 | Non-polluting transport |
| 38G | General research and development (R&D) |
| 38E | Energy research and development (R&D) |
| 40 | Refining |
| 46G | General machinery varieties |
| 46E | Energy machinery varieties |
| 47 | Other machinery |
| 50 | Ships, oil rigs, and oil-production platforms |
| 55 | Construction, excl. oil-well drilling |
| 60 | Ocean transport, and oil and gas exploration and drilling |
| 701 | Electricity from hydropower |
| 704 | Electricity from gas power without CCS |
| 705 | Electricity from gas power with CCS |
| 74 | Transmission and distribution of electricity |
| 83 | Building services |
| 90 | Central and local government |

**Appendix B**

# The model structure of firm and household behaviour

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 $i$, $j$ denotes CES composite $j$.

## The model structure of firm and household behavior

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***B.1 Production of final goods exclusive of electricity***

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

(B.4) $$C = c\left[\left(X^W\right)^{1/s} + \left(X^H\right)^{1/s}\right]$$

(B.5) $$\pi' = P^H X^H - c\left(X^H\right)^{1/s} + P^W X^W - c\left(X^W\right)^{1/s}$$

(B.6) $$P^H = \frac{c}{s}\left(X^H\right)^{\frac{1-s}{s}}$$

(B.7) $$P^W = \frac{c}{s}\left(X^W\right)^{\frac{1-s}{s}}$$

(B.8) $$s = 1/\theta$$

(B.9) $$K = \left[\delta_{KM}\left(\frac{K^M}{\delta_{KM}}\right)^{\left((\sigma_K - 1)/\sigma_K\right)} + \left(1-\delta_{KM}\right)\left(\frac{K^V}{\left(1-\delta_{KM}\right)}\right)^{\left((\sigma_K - 1)/\sigma_K\right)}\right]^{\left(\sigma_K/(\sigma_K - 1)\right)}$$

(B.10) $$K^V = \left[ \sum_{i=1}^{R} (K_i^V)^{(\sigma_{KV}-1)/\sigma_{KV}} \right]^{\sigma_{KV}/(\sigma_{KV}-1)}$$

***B.2 Production of ideas***

The two R&D industries, general and environmental, are not separated in this exposition. This is because the two industries work the same way. The same applies to the variety-capital industries below. Equations (B.1) and (B.8) apply to firms within the R&D industries. In addition, the following structure describes the industries:

(B.2') $$\pi = P_R^H X_R^H - wL$$

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

(B.4') $$C = \frac{c}{(R)^{s_1/s}} \left[X_R^H\right]^{1/s}$$

(B.11) $$R = R_{-1} + X_R^H$$

(B.5') $$\pi' = P_R^H X_R^H - \frac{c}{(R)^{s_1/s}} \left(X_R^H\right)^{1/s}$$

(B.6') $$P_R^H = \frac{c}{sR^{s_1/s}} \left(X_R^H\right)^{\frac{1-s}{s}}$$

***B.3 Production of capital varieties***

For firms producing capital varieties, Eq. (B.2) applies, in addition to the following:

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

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

(B.4'') $$C_i = c\left[\left(X_{Ki}^W\right)^{1/s}\right] + c\left[\left(X_{Ki}^H\right)^{1/s}\right]$$

(B.5'') $$\pi_i' = P_{Ki}^H \left(X_{Ki}^H\right) X_{Ki}^H - c\left(X_{Ki}^H\right)^{1/s} + P_K^W X_{Ki}^W - c\left(X_{Ki}^W\right)^{1/s}$$

(B.6'') $$P_{Ki}^{H} = m_{Ki}\frac{c}{s}\left(X_{Ki}^{H}\right)^{\frac{1-s}{s}}$$

(B.12) $$\varepsilon_{Ki} = -\frac{\partial X_{Ki}^{H}}{\partial P_{Ki}^{H}}\frac{P_{Ki}^{H}}{X_{Ki}^{H}}$$

(B.13) $$m_{ki} = \frac{\varepsilon_{Ki}}{\varepsilon_{Ki}-1} = \frac{\sigma_{Kv}}{\sigma_{Kv}-1},\ \sigma_{KV} > 1$$

(B.7'') $$P_{K}^{W} = \frac{c}{s}\left(X_{Ki}^{W}\right)^{\frac{1-s}{s}}$$

(B.14) $$P^{KV} = \left[\sum_{i=1}^{R}\left(P_{i}^{KV}\right)^{(1-\sigma_{KV})}\right]^{1/(1-\sigma_{KV})}$$

(B.15) $$P_{R0}^{H} = \int_{0}^{\infty} e^{-rt}\left(\bar{\pi}'_{it}\right)dt$$

***B.4 Consumer behavior***

(B.16) $$U_{0} = \int_{0}^{\infty} u(d_{t})e^{-\rho t}dt$$

(B.17) $$u(d_{t}) = \frac{\sigma_{d}}{\sigma_{d}-1}d^{\left(\frac{\sigma_{d}-1}{\sigma_{d}}\right)}$$

(B.18) $$W_{0} = \int_{0}^{\infty} P_{t}^{D}d_{t}e^{-rt}dt$$

(B.19) $$d_{t} = \left[\lambda \cdot P_{t}^{D}\right]^{-\sigma_{d}}$$

(B.20) $$D_{t} = d_{t}(1+n)^{t}$$

(B.21) $$D_{it} = \omega_{i.0}\left(\frac{P_{jt}^{D}}{P_{it}^{D}}\right)^{\sigma_{j}}\frac{VD_{jt}}{P_{jt}^{D}}$$

(B.22) $$\frac{D_{t+1}}{D_{t}} = (1+n)\left(1+g^{s}\right)$$

***B.5 Production of electricity***

(B.23) $$P^E = \left[ {P_{GG}^H}^{(1-\sigma_E)} + {P_{GE}^H}^{(1-\sigma_E)} \right]^{\left( 1/(1-\sigma_E) \right)}$$

(B.24) $$X_j = \left[ \frac{P^E}{P_j^H} \right]^{\sigma_E} X_G^E \text{, j=GG, GE.}$$

***B.6 Emissions***

(B.25) $$EM_{jt}^i = \varepsilon_{jt}^i \kappa_j^i A_{jt}^i$$

## B.6 Symbol list

| VARIABLES | |
|---|---|
| $PV_0$ | The present value of the representative firm |
| $\pi$ | 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 |
| $P^H$ | Domestic market price index of final good |
| $P^W$ | World market price index of final good |
| $w$ | Wage rate |
| $L$ | Labour |
| $\tau$ | Factor productivity change through international spillovers |
| $K^V$ | Variety-capital |
| $K^M$ | Other ordinary capital |
| C | The variable cost function |
| $c$ | Price index of the CES-aggregate of production factors |
| $\pi$' | Modified profit (the period-internal maximand of firms) |
| $R$ | Accumulated number of capital varieties (and of firms and patents) |
| $X_R^H$ | Production of new ideas |
| $K_i^V$ | Capital variety *i* |
| $P_i^{KV}$ | User cost index of capital variety *i* |
| $P_R^H$ | Price index of the patent |

| | | |
|---|---|---|
| $X_{Ki}^{H}$ | Output of variety firm *i* delivered to the domestic market | |
| $X_{Ki}^{W}$ | Output of variety firm *i* delivered to the export market | |
| $P_{Ki}^{H}$ | Domestic market price index of variety *i* | |
| $P_{K}^{W}$ | World market price index of varieties | |
| $P^{KV}$ | User cost index of the variety-capital composite | |
| $U_0$ | Discounted period utilities of a representative consumer | |
| $d$ | Consumption of a representative consumer | |
| $PD$ | Consumer price index | |
| $r$ | Nominal interest rate | |
| $W_0$ | Consumer's current non-human wealth + present value of labour income + net transfers | |
| $\lambda$ | 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* | |
| $g^s$ | Growth rate | |
| $\alpha_I$ | Ad val. subsidy rate on production of patents | |
| PARAMETERS | | Value |
| $s$ | Scale elasticity | 0.83 |
| $\theta$ | Transformation parameter between deliveries to the domestic and the foreign market | 1.2 |
| $\sigma_K$ | Elasticity of substitution between variety-capital and other ordinary capital | 1.5 |
| $\delta_{KM}$ | Calibrated share of other ordinary capital in the capital composite | industry-specific |
| $\sigma_{KV}$ | Uniform elasticity of substitution applying to all pairs of capital varieties | 3.0 |
| $s_I$ | Elasticity of domestic spillovers | 0.5 |
| $\varepsilon_{Ki}$ | Domestic demand elasticity for capital variety *i* | 3.0 |
| $m_{Ki}$ | Mark-up factor for variety firm *i* | 1.5 |
| $\rho$ | Consumer's rate of time preferences | 0.04 |
| $\sigma_d$ | Intertemporal elasticity of substitution | 0.3 |
| $\omega_{i.0}$ | Budget share of good *i* in CES aggregate *j* in period 0 | good-specific |
| $\sigma_j$ | Elasticity of substitution between the two consumer goods in CES aggregate *j* | 0.5 for all j |

**Figure B.1. The nested structure of the production technology**

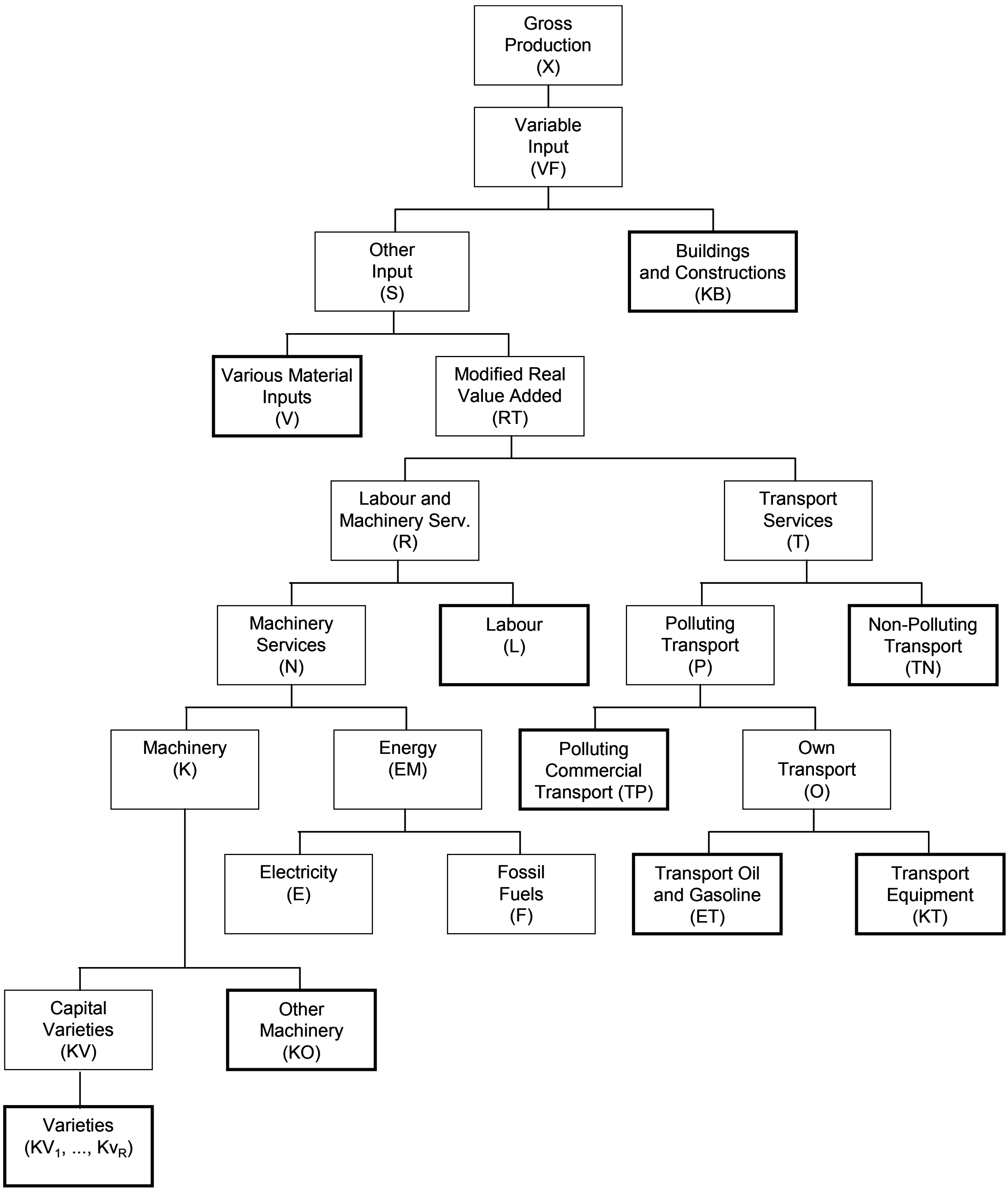


**Figure B.4. The nested structure of consumption activities**

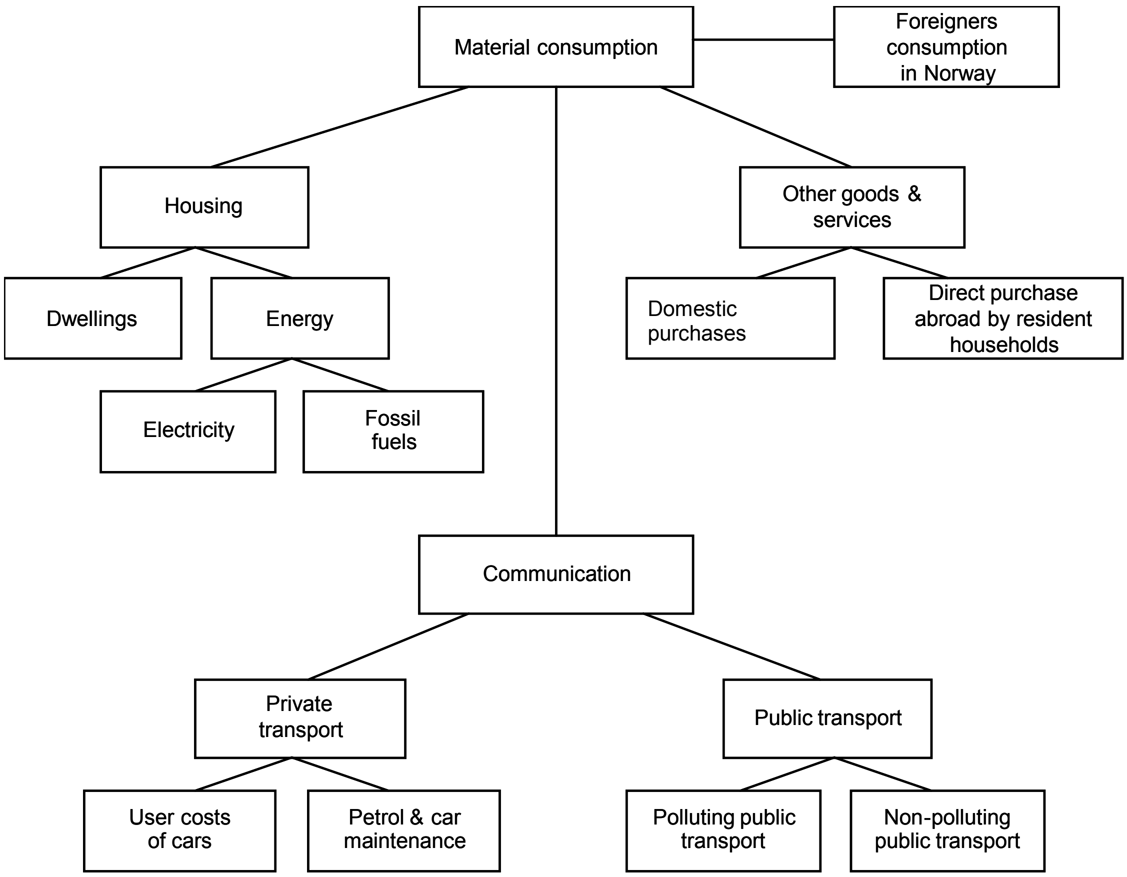


**Figure B.2: The nested structure of the production technologies for the gas power sectors**

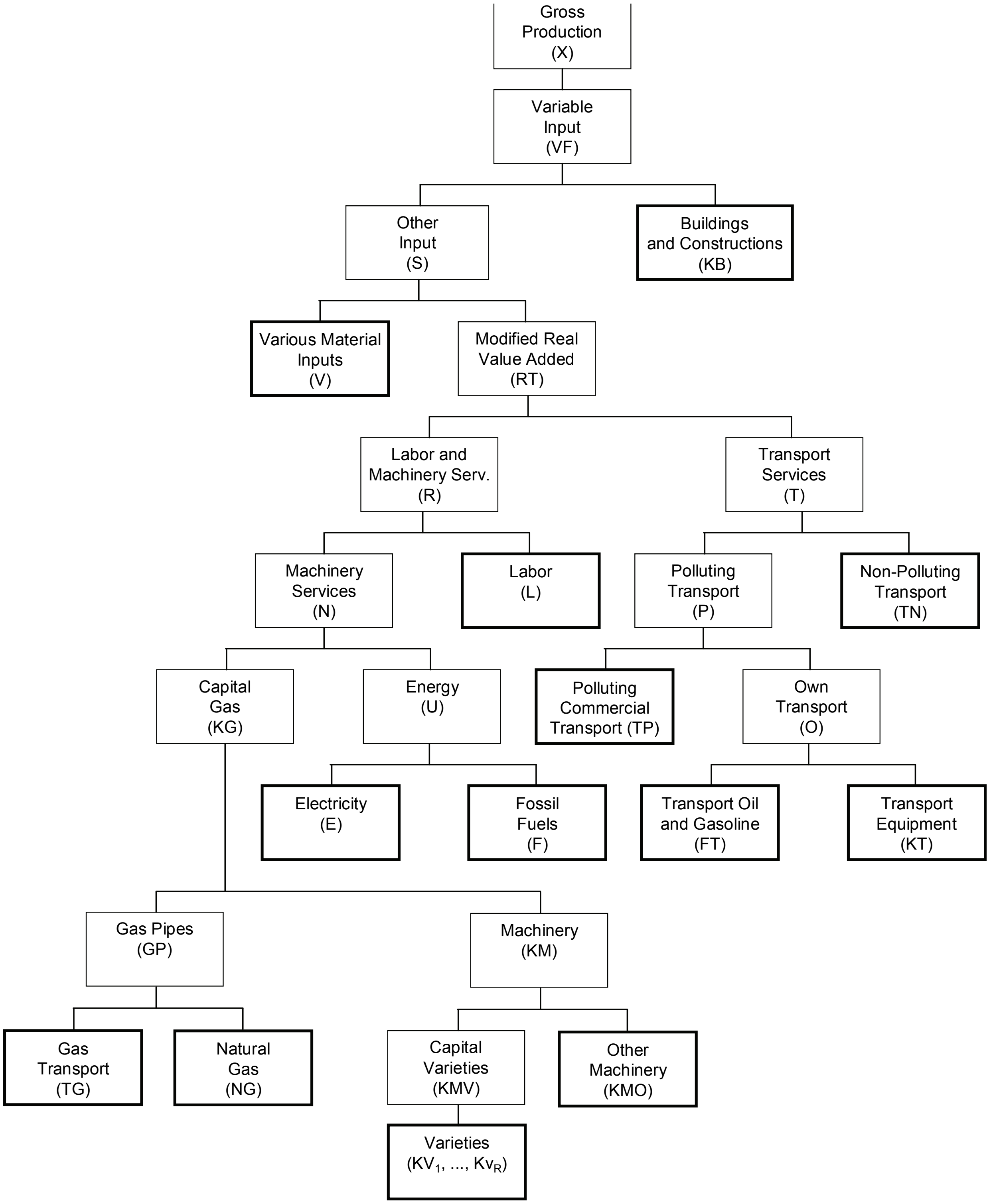
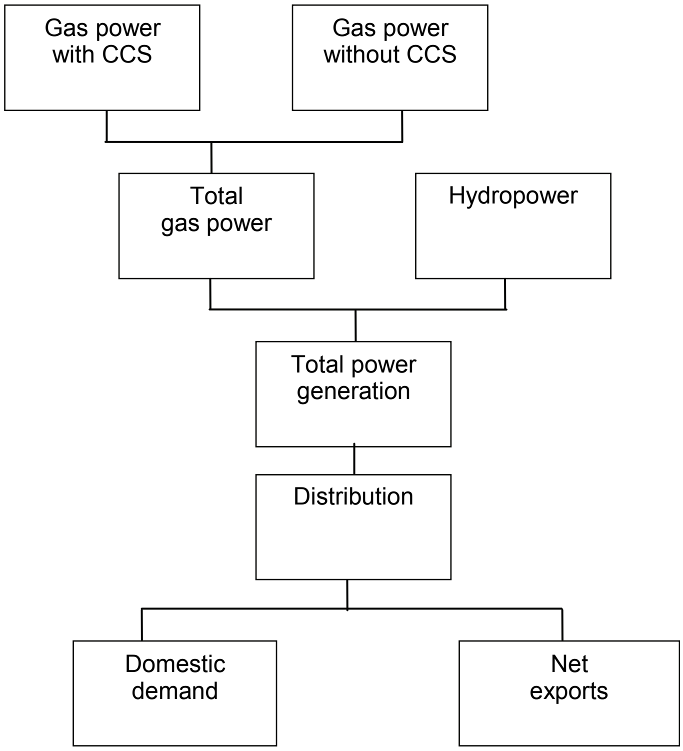


**Figure B.3 The electricity market**



**Appendix E**

# The price of electricity and the production costs of gas power

The cost structure in the model gives a producer price of electricity delivered from the CCS gas power industry of 0.07 €/kWh in 2002.[28] From the gas power industry without CCS the price is 0.045 €/kWh. The producer price of electricity delivered to the market in the calibrated year is 0.028 €/kWh. To keep production levels in the gas power industries at the calibrated level, their producer prices are subsidized in 2002 with 0.043 €/kWh and 0.016 €/kWh, for production with and without CCS, respectively. These subsidies are phased out during the first 10 years. This is compatible with positive and increasing output from the two gas power industries along the path, as the demand for electricity is increasing.

The costs presented here are sensitive to the price of gas. The model is calibrated to a gas price of 0.14 €/$Sm^3$ in 2002. For a higher gas price, both the gas power industries face higher costs. Though, the cost difference is smaller for a higher gas price, since the gas factor input share is smaller for the CCS plants, confer section 3.1 for more details on cost shares in gas power production with CCS.

[28] 1 € = 6.97 NOK, 1 $=7.29 NOK, 31. December 2002.