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Long-Run Effects of Post-Kyoto Policies: Applying a Fully Dynamic CGE model with Heterogeneous Capital

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April 2010

Abstract

The paper develops a new type of CGE model to predict the effects of carbon policies on consumption, welfare, and sectoral development in the long run. Growth is fully endogenous, based on increasing specialization in capital varieties, and specific in each sector of the economy. The benchmark scenario is calculated based on the endogenous gains from specialization which carry over to policy simulation. Applying the model to the Swiss economy we find that a carbon policy following the Copenhagen Accord entails a moderate but not negligible welfare loss compared to development without any negative effects of climate change. Energy extensive as well as capital and knowledge intensive sectors profit in the form of increased growth rates.

Keywords: Carbon policy, CGE models, energy and endogenous growth, heterogeneous capital

JEL Classification: Q54, C63, O41, Q43, Q56

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1 Introduction

At the climate summit in Copenhagen, the conference of the parties (COP 15) took note of the Copenhagen Accord, which calls for a stabilization of the greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Specifically, the increase in global temperature should be below 2 degrees Celsius. In order to reach this target, CO₂ reductions for industrialized countries should be in a range of -25% to -40% by 2020, and -80% to -95% by 2050. The benefit of these policies lies in (sharply) reducing the probability of large damages due to climate change. The involved costs are related to the induced change in economic growth. They have to be evaluated with the help of adequate quantitative models, which are based on energy input and aimed at predicting development in the long run.

This paper develops and uses the Computable Induced Technical change and Energy (CITE) model to predict the long-run effects of stringent carbon policies on consumption, welfare, and sectoral development. Because the accuracy of long-term predictions crucially depends on the quality of the included growth mechanism, the CITE model relies on the achievements of new growth theory, specifically on Romer (1990) and Grossman and Helpman (1991). The incentives to invest in the expansion in capital varieties arise endogenously and provide the basic mechanism for productivity and consumption growth. A key feature of the model is that it includes the gains from specialization already in the benchmark scenario, so that the growth mechanism is consistent among all the different scenarios. Furthermore, endogenous growth is determined for each sector separately. By capturing the sectoral differences in energy intensities, the complex linkages between the sectors, and the sector-specific investment behavior, a rich development pattern can be depicted by the model.

We apply the CITE model to the Swiss economy and find that climate policies following the Copenhagen Accord do not prevent consumption and sectoral outputs from growing in the future. Compared to business-as-usual without climate change, the consumption level in 2050 is 4.5 % lower and discounted welfare decreases by 2.6 %. However, the absence of any negative effects of climate change is not realistic: the development with undamped climate change is likely to entail higher losses and especially higher risks in the long run, see Stern (2007). An appropriate cost-benefit analysis has to compare the costs of action with the costs of inaction, including all types of uncertainties. According to the expectation from theory and confirming the validity of the model, energy extensive as well as capital and knowledge intensive sectors profit in the form of increased growth rates.

The paper builds on the fact that long-run development is best predicted by a fully dynamic model. Since the seminal work of Solow (1956), economists view capital and technology as the main drivers of economic growth. Moreover, increasing gains from specialization foster economic development. This insight goes back to Adam Smith who calculated 250 years ago already how much the division of labor increases the efficiency of the labor force. Gains from specialization were formally included in economic models by Spence (1976), Dixit and

Stiglitz (1977), and Ethier (1982) who refined the approach by assuming that an increasing number of intermediate inputs to production would raise output. Endogenous growth through increasing specialization lies at the heart of one strand of so-called "new growth theory", see Romer (1987, 1990), where output is an increasing function of intermediate goods and new intermediate goods need innovations as up-front investments. Adding the investment decisions and (strong enough) learning spillovers, growth becomes endogenous and continues indefinitely.

Spillovers have also played a role in previous CGE models, where learning curves are used extensively, see e.g. Messner (1997) and Grübler and Messner (1998). Endogenous research has been included more recently. Nordhaus (2002) introduces R&D in his DICE model (R&DICE) and includes two forms of technological change, an economy-wide technological change and a carbon-energy-saving technological change. Buonanno et al. (2001) enhance the RICE model of Nordhaus & Yang (1996) and include induced technical change. The impact of induced technical change has also been treated in Popp (2004), Kemfert (2002), Gerlagh (2007), Goulder and Schneider (1999), Goulder and Mathai (2000), Edenhofer et al. (2005), and Bosetti et al. (2006).

This paper adds to the literature by relating the dynamics of CGE models to endogenous growth theory, applying the framework of gains from specialization. Capital is heterogeneous, the capital variants grow in quantity and number through physical capital investments and innovative activities. The simulation of the model delivers results on the long-run macroeconomic effects of climate policy, which are relevant for current and future energy and carbon policy. The remainder of the paper is organized as follows. Section 2 provides the theoretical foundation of the used CITE model. In section 3, the data and the parameters are explained. Section 4 presents the results for the post-Kyoto carbon policy for Switzerland. Section 5 concludes.

2 Theoretical framework

This section introduces the CITE model and presents its specific features guiding the subsequent simulation of carbon policies.¹ The biggest challenge of modelling is the adequate integration of the expansion-in varieties mechanism of new growth theory into a dynamic simulation model with many sectors and energy as a main input.

2.1 Producers

The production sector specifies sectoral manufacturing and input substitution as well as the whole set intersectoral linkages in a multisector economy. All final goods of a sector are used in the production of all the goods, including their own production. As the energy and the oil sectors differ from the other sectors, we use two different labels for the sectors: regular

¹To keep the exposition short, only the main elements are presented here; for further details see Schwark (2010a, 2010b).

sectors excluding energy and oil are labelled by the index n while the index for all the sectors is i . Final goods Y in sector n , Y_n ($n \in N$), are manufactured under the conditions of CES production functions using two types of inputs: a sector-specific intermediate composite Q_n and output from sectors n' , $A_{n'n}$ ($n' \in N$):

$$Y_{n,t} = \left[\alpha_{X,n} Q_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1 - \alpha_{X,n}) \left(\min \left(\left\{ \frac{A_{n'n,t}}{a_{n'n}} \right\}_{n' \in N} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}} \quad (1)$$

The label A reflects that goods are distinguished according to origin, i.e. they are so-called "Armington" goods which is the usual assumption in numerical simulation models. (1) reflects that all final goods are used in the production of all the goods. The elasticity of substitution between Q_n and $Y_{n'n}$, $\sigma_{Y,n}$, is assumed to be smaller than unity to reflect limited substitution possibilities between the intermediate composite and final goods as inputs. The value share of the intermediate composite is $\alpha_{X,n}$. The activity coefficients $a_{n'n}$ give the amount of each Armington good $A_{n'n}$ that is required for one unit of output in the Leontief function. We chose Leontief as we consider the substitutability of these Armington goods in the production as very weak. The energy and the oil sector produce with the same production functions, except from the fact that the energy sector uses imported gas and the "Armington good" of the oil sector as inputs. The oil sector additionally needs imported crude oil for production. Each sectoral producer of a regular final good maximizes profit under the restrictions (1):

$$\max_{Q_{n,t}, A_{n'n,t}} p_{Y_n,t} Y_{n,t} - p_{Q_n,t} Q_{n,t} - \sum_{n' \in N} p_{A_{n'n},t} A_{n'n,t} \quad (2)$$

subject to (1) with p_H denoting the price for variable H . As the market for final goods is perfectly competitive, profits are zero and the inverse demand functions given by:

$$p_{Q_n,t} = p_{Y_n,t} \alpha_{X,n} \left(\frac{Y_{n,t}}{Q_{n,t}} \right)^{\frac{1}{\sigma_{Y,n}}} \quad (3)$$

and, respectively,

$$p_{A_{n'n},t} = p_{Y_n,t} (1 - \alpha_{X,n}) \left(\frac{Y_{n,t}}{\min \left(\left\{ \frac{A_{n'n,t}}{a_{n'n}} \right\}_{n' \in N} \right)} \right)^{\frac{1}{\sigma_{Y,n}}} D_{n'n} \quad (4)$$

with $D_{n'n}$ being the derivative of the Leontief production structure w.r.t. the input of sector n' to sector n . The growth rate of the economy depends on the growth rates of the sectors. These, in turn, result from an increase of the varieties of sectoral intermediate goods, which is reflected in the production of the sectoral intermediate composite Q_i . It is produced with a Dixit-Stiglitz production function, reading:

$$Q_{i,t} = \left[\int_{j=0}^{K_{i,t}} x_{ij,t}^{\kappa} \right]^{\frac{1}{\kappa}} \quad (5)$$

with $0 < \kappa < 1$ and x_{ij} as the employment of the j th type of specialized intermediate good. K_i measures the number of intermediates available in sector i . Each intermediate good needs one unit of capital in order to be produced so that K_i is at the same time a measure of the sector specific capital stock. Q_i can be raised by an increase of x_{ij} or K_i , which provides additional diversification and thus increases the productivity by exploiting gains from diversification. κ is a measure for the substitutability of the intermediate goods with $\kappa = (\sigma_Q - 1) / \sigma_Q$ and $\sigma_Q > 1$ being the elasticity of substitution between the intermediate goods. On a competitive market, the intermediate composite producer maximizes profits according to

$$\max_{x_{ij,t}} p_{Q_i,t} Q_{i,t} - \int_{j=0}^{K_{i,t}} p_{x_{ij,t}} x_{ij,t} \quad (6)$$

subject to (5) which yields her optimal demand for intermediate good x_{ij}

$$x_{ij,t} = \left(\frac{p_{Q_i,t}}{p_{x_{ij,t}}} \right)^{\frac{1}{1-\kappa}} Q_{i,t} \quad (7)$$

Intermediate goods $x_{ij,t}$ are produced by firms that face a CES production function and use the inputs labor L_{ij} , non-accumulable capital VK_{ij} , and energy $A_{ex_{ij}}$

$$x_{ij,t} = \left[\alpha_{L,i} L_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1 - \alpha_{L,i} - \alpha_{VK,i}) A_{ex_{ij,t}}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} \right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}} \quad (8)$$

We introduce VK_{ij} in order to satisfy the equilibrium conditions for a balanced growth path with heterogeneous sectors. Balanced growth is a useful assumption for the benchmark but can only be obtained with identical capital shares between the sectors. To establish equal sector shares at the beginning we introduce the additional input VK_{ij} which does not grow and thus has no impact on the dynamics of the economy when doing policy simulations (see Section 3 for details). To determine $p_{x_{ij,t}}$, there is a mark-up over marginal costs (given by $1/\kappa$) because intermediate goods are imperfect substitutes for each other. The profits from x -production are used to compensate for capital investments, which are the prerequisite for the production of a new intermediate.

The number of capital varieties is increased by investments in physical capital ($I_{P_{ij}}$) and non-physical capital ($I_{NP_{ij}}$). Both types of investment are sector specific. Non-physical investments are effectuated by labor input in research, RL_{ij} and investments in R&D, $I_{R\&D,ij}$:²

$$I_{NP_{ij,t}} = \left[\gamma_{N,i} RL_{ij,t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}} + (1 - \gamma_{N,i}) I_{R\&D,ij,t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}} \right]^{\frac{\sigma_{N,i}}{\sigma_{N,i}-1}} \quad (9)$$

Together with investments in physical capital, $I_{P_{ij}}$, non-physical investments $I_{NP_{ij,t}}$ determine capital in the next period according to

²The formulation of $I_{R\&D,ij}$ stems from the fact that below we apply data for R&D investments from the Swiss input-output-table for $I_{R\&D,ij}$. It is not identical to the general R&D-activity in the production process.

$$K_{ij,t+1} = \left[\gamma_i I_{P_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} + (1-\delta) K_{ij,t} \quad (10)$$

δ depicts the depreciation rate of capital. The growth index g_K of the capital composite of sector i then amounts to:

$$g_{K_i} = \frac{K_{i,t+1}}{K_{i,t}} = \frac{\left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}}}{K_{i,t}} + (1-\delta) \quad (11)$$

2.2 Consumers

A representative, infinitely-lived household allocates income between consumption and investment in accordance with intertemporal utility maximization under perfect foresight. It faces an additively separable intertemporal utility function U with consumption good C yielding utility and ρ denoting the discount rate of the household³

$$U = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t C_t^{1-\theta} \right]^{\frac{1}{1-\theta}} \quad (12)$$

The consumption good is composed of a final good composite C_S and energy A_{ec}

$$C_t = \left[(1-\beta) C_{S,t}^{\frac{\sigma_C-1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C-1}{\sigma_C}} \right]^{\frac{\sigma_C}{\sigma_C-1}} \quad (13)$$

The final goods of all the different sectors determine the final good composite according to

$$C_{S,t} = \prod_{n \in N} A_{nc,t}^{\beta_{NE,n}} \quad (14)$$

with A_{nC} denoting the part of regular final good n that goes into consumption and $\beta_{NE,n}$ being the share of final good n in the final good composite. We further assume $\sum_{n \in N} \beta_{NE,n} = 1$.

In order to indicate the dynamic behavior of consumption, the prices of the consumption good and the final good composite are applied for the calculation, which read

$$p_{C,t} = \left[(1-\beta)^{\sigma_C} p_{C_S,t}^{1-\sigma_C} + \beta^{\sigma_C} p_{A_{ec},t}^{1-\sigma_C} \right]^{\frac{1}{1-\sigma_C}} \quad (15)$$

$$p_{C_S,t} = \prod_{n \in N} \left(\frac{p_{A_n,t}}{\beta_{NE,n}} \right)^{\beta_{NE,n}} \quad (16)$$

Accordingly, the household faces the budget constraint

³This utility function is useful for numerical simulation; it has the same intertemporal characteristics as the better known CIES function) $U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t \frac{C_t^{1-\theta}-1}{1-\theta}$, see Rutherford (2004).

$$\begin{aligned}
p_{V,t+1}V_{t+1} &= (1 + r_{t+1})p_{V,t}V_t + w_tL_t + w_{R,t}RL_t + p_{VK,t}VK_t \\
&\quad - p_{C,t}C_t - \sum_{i \in I} p_{V,t}I_{i,t}
\end{aligned} \tag{17}$$

Hereby, V denotes the assets of the household. Total investments of the household must equal investments in physical and in non-physical capital, $I_{i,t} = I_{P_i,t} + I_{NP_i,t}$. As energy is assumed to be a factor that is owned by the consumer, income from energy also goes to the consumer as factor income. The budget constraint is explicitly modeled such that income from endowments and capital is equal to consumption plus investments. The augmented Lagrangian for the optimization problem of the household is

$$\begin{aligned}
\mathfrak{L} &= \frac{C_t^{1-\theta} - 1}{1-\theta} + \frac{1}{1+\rho} \lambda_{t+1} ((1 + r_{t+1})p_{V,t}V_t + w_tL_t + w_{R,t}RL_t \\
&\quad + p_{VK,t}VK_t - p_{C,t}C_t - \sum_{i \in I} p_{V,t}I_{i,t}) - \lambda_t p_{V,t}V_t
\end{aligned} \tag{18}$$

where the maximization yields

$$C_t^{-\theta} = \frac{1}{1+\rho} \lambda_{t+1} p_{C,t} \tag{19}$$

$$\lambda_t = \frac{1}{1+\rho} \lambda_{t+1} (1 + r_{t+1}) \tag{20}$$

with $\lambda > 0$ being the shadow price of consumption. From the first order conditions of household optimization we can calculate the growth index of consumption g_C

$$g_C = \left[\frac{1 + r_{t+2}}{1 + \rho} \frac{p_{C,t}}{p_{C,t+1}} \right]^{\frac{1}{\theta}} \tag{21}$$

2.3 Growth

Economic growth is determined by the growth rate of the capital stock, which reflects investment decisions of the representative household. If $g_H = \frac{H_{t+1}}{H_t}$ denotes the growth index of variable H , the growth index of consumption can be derived by dividing consumption in period $t + 1$ through consumption in period t :

$$g_C = \left(\frac{(1 - \beta)C_{S,t+1}^{\frac{\sigma_C-1}{\sigma_C}} + \beta A_{ec,t+1}^{\frac{\sigma_C-1}{\sigma_C}}}{(1 - \beta)C_{S,t}^{\frac{\sigma_C-1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C-1}{\sigma_C}}} \right)^{\frac{\sigma_C}{\sigma_C-1}} \tag{22}$$

Using $\overline{g_H} = \left(\frac{H_{t+1}}{H_t} \right)^{\frac{\sigma_C-1}{\sigma_C}}$ for an adjusted growth index the above equation can be simplified and the adjusted growth rate of consumption can be reformulated as

$$\overline{g_C} = \psi_{C_S} \overline{g_{C_S}} + \psi_{A_{ec}} \overline{g_{A_{ec}}} \tag{23}$$

with

$$\psi_{C_S} = \frac{1 - \beta}{(1 - \beta) + \beta \left(\frac{A_{ec,t}}{C_{S,t}} \right)^{\frac{\sigma_C - 1}{\sigma_C}}} \quad (24)$$

$$\psi_{A_{ec}} = \frac{\beta}{(1 - \beta) \left(\frac{C_{S,t}}{A_{ec,t}} \right)^{\frac{\sigma_C - 1}{\sigma_C}} + \beta} \quad (25)$$

where $\psi_{A_{ec}} = 1 - \psi_{C_S}$. On a balanced growth path, C_S must grow at the same rate as C and A_{ec} .⁴ Also, it can be shown that:

$$g_{C_S} = \prod_{n \in N} (g_{Y_{nc}})^{\beta_{NE,n}} \quad (26)$$

The growth index of Q_i can be calculated straightforward. Given its production function and the growth index of capital from (11), and applying a similar calculation as above, g_{Q_i} is equal to

$$g_{Q_i} = \left[\frac{\left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1 - \gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}}}{K_{i,t}} + (1 - \delta) \right]^{\frac{1}{\kappa}} g_{x_i} = g_{K_i}^{\frac{1}{\kappa}} g_{x_i} \quad (27)$$

As the growth of the intermediate goods equals zero and therefore the growth index g_{x_i} must be one, (27) is equal to

$$g_{Q_i} = g_{K_i}^{\frac{1}{\kappa}} \quad (28)$$

The above equation is the central relation in the model as it ensures endogenous growth through gains of specialization in the production of intermediate goods. The economy is able to grow even without growth of the inputs to intermediate goods, i.e. labor and energy. With this and by modeling international trade with additional Armington goods as usual in the literature⁵ we are ready to use the model for numerical simulation.

3 Data and Parameters

3.1 Data

For the simulation we use data from the Swiss input-output table (hereafter named IOT) for the year 2005 (Nathani, van Nieuwkoop and Wickart (2008)), which is the most recent version available. It gives detailed information on the flow of goods between sectors and to final demand and also on the use of inputs and on trade. The original table holds data for 42

⁴See Schwark (2010a) for details.

⁵see Schwark (2010a).

production sectors and differentiates between fifteen types of consumption (twelve for private households, three for public consumption) and three types of physical investments. As for the use of factor inputs, it holds information on the use of labor and capital. It is therefore an almost complete source of data for the type of model we are using.

For the purpose of our model, the original IOT was aggregated to 12 sectors (10 regular sectors, an energy sector and an oil sector).⁶ The model distinguishes two types of investments, physical and non-physical investments. Non-physical investments mainly refers to investments in research and development. The original IOT contains no information on these types of investments. Additionally, there is no reliable data available in Switzerland, especially not on a sectoral level. We therefore use the data from sector 73 ("Research & Development") to have a measure for these investments. Put differently, we interpret the demand for goods from sector 73, i.e. the row entries of this sector, as investments in R&D of the sectors demanding these goods. To represent this interpretation in the IOT, we transferred these entries into a new column (R&D investments). The column entries of sector 73 and its imports, exports, value added, consumption and investments were added to other services (OSE), except for the entry of labor. We use this entry as our benchmark value for research labor (LH). With this procedure, we get sectoral values for R&D investments and an aggregate measure of research labor. Research labor is then redivided to the sectors according to their share in total capital use. This gives us a value for initial sectoral demand for research labor.

Furthermore, capital had to be split into two capital types, labeled K (accumulable capital) and VK (non-accumulable capital). In the benchmark, the model is calibrated to a balanced growth path, implying that all sectors grow at the same rate. This calibration requires that the share of capital $(1 - \kappa)$ in the production of intermediate goods has to be equal in all sectors. The reason for this is that the capital share (or the gains of specialization) directly affects the sectoral growth rates. Different capital shares would therefore imply different rates of growth, which would not be consistent with the calibration. In the original data, there are obviously large differences in these shares. We solve this issue by setting the values of accumulable capital (K) so that its share is equal in all sectors and by defining the residual of initial capital as another input to intermediate production. K is the part of total capital that can be accumulated via investments, while VK enters production of intermediate goods at the same level as labor and energy and cannot be accumulated. VK can be thought of as publicly provided capital (e.g. public infrastructure or services) in the sense of Barro (1990). While helping to solve the benchmark calibration simulations show that VK has no distorting effect on the quality of the results.

3.2 Parameters

The choice of parameter values, most notably of the elasticities of substitution, may have a substantial influence on the model results. It is therefore important to choose these values

⁶see Ramer (2010a) for details.

carefully and reasonably. The elasticities of substitution are set in accordance with given empirical estimations and studies (see e.g. Van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process and Hasanov (2007) for estimates for the intertemporal elasticity of substitution in the utility function). Sectoral differences in substitutability of inputs on the different levels of the production process are taken into account by setting sectorally differentiated values for the corresponding elasticities whenever available and reasonable. An overview of the elasticities used is given in the appendix. We also carefully performed a sensitivity analysis to check the robustness of the model results with respect to variations of the values of the elasticities. The results prove to be robust, see Ramer (2010b) for details.

From Table 1, see the appendix, it can be seen that most values for the elasticities are set below unity. Exceptions are the trade elasticities and $\sigma_{Y,CON}$. This implies a certain rigidity, especially in the production process, and possibly limits the effects of political intervention as inputs are not well substitutable on certain levels. There are two comments on this. Most of the values are based on given estimations that prove that substitution possibilities are indeed limited⁷. And, secondly, our model is still relatively flexible in comparison to other models (e.g. Ecoplan (2007)), who are even more stringent as far as the values for the elasticities in the production processes are concerned. The Armington elasticities differ from the rest in the sense that they are all set considerably above one. This basically reflects the fact that it is of limited relevance where the goods have been produced, irrespective of whether they are used in production or consumed. This seems to be a reasonable assumption and is also common in similar studies.

The model is calibrated such that it reflects both projected output growth and growth rates of the capital input. To be more precise, we assume that capital grows at an annual rate of 1%. This matches the observed growth rate of capital goods in Switzerland since 1990. In our calibration, in combination with the before mentioned share of capital $(1 - \kappa)$, this leads to annual growth rate of about 1.33%, which is in line with the rate assumed in the high GDP scenario of the Energy Perspectives. The share of capital essentially defines the intensity of the spill-overs (i.e. the gains of specializations) and therefore also defines the difference between the growth rate of the inputs and the projected output growth rate. $(1 - \kappa)$ is set to 0.25 in all sectors. Capital depreciates at a rate starting at 0.04. This rate rises by a small amount every year, due the fact that capital and investments grow at different rates in the model. To be able to calibrate the model correctly, we have to use a non-constant depreciation rate. Using a calibration procedure by Paltsev (2004), we can then derive the interest rate r (given the depreciation rate and the benchmark values for the capital stock and investments). Given the values in our model, the interest rate is about 0.016 or 1.6%.

An important point to consider when interpreting the aggregate effects is that our bench-

⁷Van der Werf (2007) e.g. tests for Cobb-Douglas functions (i.e. an elasticity of substitution of 1) as a representation of the substitutability between labor, energy and capital and shows that it is not an empirically valid assumption.

mark scenario is not a realistic business-as-usual case, because it abstracts from climate change and its possible negative effects. A benchmark path that comes closer to reality would thus be one that considers climate change, but does not include any political intervention. The Stern Report includes projections of losses in GDP per capita, given undamped climate change. Due to the long time horizon of these projections, there is obviously a considerable uncertainty on the effects on per capita GDP, and the range of possible long-term impacts is large. However, it seems clear that especially in later decades, the losses increase sharply in the absence of political intervention. Depending on the assumptions on the impacts of climate change and on what other effects are considered, losses could augment up to 35% in 2200. Policy measures aiming at mitigating climate change should thus be able to significantly reduce these losses in later decades. Thus, although it may lead to larger losses in the shorter term, implementing policy measures that mitigate climate change should be beneficial as possibly even larger losses in the long run can be avoided or at least reduced.

4 Simulation Results

We analyze the relatively stringent Copenhagen targets for Switzerland, without the possibility of abatement offsets abroad. These targets are based on the the agreement that the increase in global temperature should be limited to 2 degrees Celsius. We introduce a CO2 tax in such a way that carbon emissions are reduced by 30% in 2020 and by 80% in 2050. The tax is levied on the two fossil energy inputs (oil and gas), where oil is taxed at a higher rate due to its higher CO2 intensity. The results are shown in Figures 1 and 2.

Given the ambition of the target and the stringency of the policy, one would expect strong impacts on consumption and welfare. However, this is not the case. The effects on consumption and welfare are moderate. Welfare, which is measured by total discounted consumption over the entire model horizon, decreases by 2.6%. The discount rate is about 1.1%, which is a comparably low value. Consumption over time declines steadily as long as the tax is rising (i.e. until 2050 when the reduction target is reached), but at a small scale. In 2020 (when the intermediate target of a 30% reduction is reached), consumption is reduced by slightly more than 1%. In 2050, it is about 4.5% lower than in the benchmark. This confirms previous findings that even relatively stringent policies are economically feasible from a consumer point of view.

**** Figure 1 ****
about here

Both consumption over time and overall welfare are only affected moderately, implying that even restrictive policy measures come at a bearable cost. Figure 1 compares the growth path of consumption with the benchmark path and highlights that the deviation from the benchmark path is moderate. The level of consumption reached in 2050 in the scenario with

the CO2 tax is reached about 2.5 years earlier in the benchmark case. One reason for this moderate effect is that the share of energy in total consumption is only 2% and therefore very small. Another reason lies in the induced growth effects. The direct effect of the tax through an increase in the relative price of energy goods is thus only minimal. The CO2 tax also affects the prices of non-energy goods, because they use energy as an input to production. Non-energy goods enter consumption on the second level of the nested function and are assumed to be good substitutes, implying that the household has a relatively flexible consumption structure that facilitates substitution of energy intensive for non-energy intensive goods.

**** Figure 2 ****
about here

At the sectoral level, the introduction of the tax leads to pronounced structural effects (see Figure 2). Reactions in sectoral output range from an increase of about 35% in the machinery industry to a decrease of more than 25% in other industries, compared to the benchmark scenario. Three sectors have a higher output level in 2050 than in the absence of a CO2 tax, the remaining sectors are either not much affected or suffer losses. The biggest gainer of the policy is the machinery industry. It increases its output by about 35% until 2050. The chemical industry and insurances also benefit from the introduction of the CO2 tax. The chemical industry gains slightly less than 10%, insurances about 1%. Several sectors incur small losses in the range of 2% to 4%. These sectors include construction and most service sectors (other services, health and banking and financial services). The sectors that lose more than 10% or even 20% (apart from the energy sector and the oil sector, which are not shown in the graph) by 2050 are other industries, agriculture and transport.

There are various reasons for these structural changes. First, and most importantly, certain sectors benefit from the substitution of capital for energy and the associated increased investments. Physical investments require inputs from industries such as the machinery industry. As capital stocks and thus investments increase significantly in certain sectors, industries providing investment goods naturally have a large benefit. Moreover, the machinery industry and the chemical sector are very capital and knowledge intensive themselves, which supports their position as winning sectors. Interestingly, their growth rates are higher than in the benchmark case and this right from the beginning, which exhibits the importance of forward looking agents.

A second explanation is the energy intensity of the sectors, i.e. the relative importance of energy as an input in the production of output of a sector. As energy enters sectoral production at the level of the intermediate varieties, we measure the energy intensity by the share of energy used in the production of the intermediate varieties ($(1 - \alpha_L - \alpha_{VK})$ in model parameters). The more energy a sector uses in its production process, the more it is exposed to the tax (because the tax is levied on fossil energy) and the more it should be affected by the tax. Transports, agriculture and other industries all have an energy share around 10%, which makes them the three most energy intensive sectors in the economy. Thus, the

three sectors that have the highest energy intensity are those that suffer the largest losses. Construction also decreases its output, but at a smaller scale. Its energy intensity is just below 5%, which is the highest share after the three sectors discussed above. The negative effect on the construction sector may however be overestimated in this model, because an important aspect of Swiss energy policy is excluded. Increased standards for energy efficiency for new buildings and corresponding regulations for the renovation of existing infrastructure are an important aspect of future reductions in energy demand. These regulations should clearly be favorable for the construction sector if they were included in the model, as the demand for construction services should increase significantly. This mechanism being excluded, the decrease in output of the construction sector can be readily explained by its relatively high energy intensity.

The service sectors on the other hand generally have very low energy intensities. Their shares are in a range between 2.6% for other services to 0.6% for banking and financial services. These low values show that services are clearly less exposed to the tax, and therefore their reactions to the tax are very small. The fact that their output still slightly decreases can be explained by their comparably low substitution possibilities. For the service sectors, we assume a lower elasticity of substitution between the inputs in the production of the intermediate varieties. The potential to avoid the tax is smaller than other sectors, most notably than in the two industries that benefit from the introduction of the CO₂-tax. This leads to a small decrease in output of most service sectors, despite the low energy shares. The machinery industry and the chemical industry also use relatively little energy in their production (the machinery industry has a high labor share, the chemical industry is very capital intensive), and they both have better substitution possibilities for energy than the service sectors (reflected by higher values of σ_X). These two characteristics give them a comparative advantage over the other sectors and enable them to benefit from the policy.

A final reason for the structural changes are the linkages of the different sectors to the energy sector and the oil sector. These linkages are reflected in the use of outputs of other sectors in the production process. As the oil sector and the energy sector reduce their output by a substantial amount due to the tax, they also require fewer inputs from the other sectors.

The capital stocks (not shown here) exhibit a similar pattern as output, which means that there is a clear indication that capital is shifted to the non-energy intensive sectors. The non-energy intensive sectors are more attractive for investors in the presence of the CO₂-tax, because they are less affected by the tax. This leads to higher investments and an increase in their capital stocks. Due to the direct link between capital accumulation and sectoral development, the resulting sectoral growth rates vary considerably. But, despite the ambitious reduction target, all sectors still exhibit positive growth rates, even if they perform worse than in the benchmark.

To corroborate the results we have performed other policy simulations with the CITE model. We have changed the time horizon to 2035 which, according to the expectation, caused less welfare costs than those for 2050. We also found that distribution of tax revenues

has an impact on consumption and welfare which depends on the considered time horizon; for a shorter time horizon, research subsidies cannot develop their full advantages for the economy while in the long run, these subsidies are superior to the redistribution of revenues to households. For the small open economy Switzerland it makes a difference which policies are implemented in the other countries. Finally, a larger population must reduce carbon emissions per capita more sharply so that the negative welfare effects are seen in more pronounced way.

5 Conclusions

To evaluate the long-run effects of climate policies, the paper integrates the achievements of endogenous growth theory into CGE modeling. The continuous and sector-specific expansion in capital varieties provides the basic mechanism for long-run development. We find that the fulfillment of the carbon reduction commitments of the Copenhagen Accord in Switzerland causes net welfare costs which are quite moderate but not negligible. It is plausible to argue that - in view of these effects - such a climate policy be advocated, because the costs of undamped climate change are likely to be higher. Considering the low discount rate and the stringency of the studied carbon policy, a welfare reduction of 2.6% seems to be a relatively moderate cost. This especially applies when the risks of large natural catastrophes can be substantially reduced by appropriate policy interventions. But, of course, this assumes that the world as a whole acts according to the Copenhagen Accord; only this entails the desired effect on global emissions. Sectoral differences in the simulated growth rates are significant; they reflect energy intensities, sectoral linkages, and distinct specialization in capital goods.

The model assumptions are conservative in several respects. Technology development is modeled in a top-down manner, which excludes the consideration of specific potential technologies that might be highly influential on energy efficiency. Learning effects are not a focus; accordingly, the build-up of new core competencies to be used as a comparative advantage in international trade does not emerge. Finally, all elasticities and parameter values are assumed in a conservative way.

To complete the evaluation of climate one would have to add secondary benefits of energy and carbon policy, such as positive effects on health and local pollution. In addition, the extension of this endogenous growth model to a full-fledged multi-region model would be desirable. This is left for future research.

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7 Appendix

Parameter	Description	Value
$\sigma_{Y,i}$	Elasticity of substitution between Q and inputs from other sectors	0.392 (AGR) 0.848 (OIL, CHM) 0.518 (MCH) 0.100 (EGY) 1.264 (CON) 0.352 (TRN) 0.568 (OIN) 0.492 (rest)
$\sigma_{X,i}$	Elasticity of substitution between the three inputs (energy, labor and VK)	0.7 (AGR, OIL, CHM, EGY) 0.8 (MCH) 0.52 (CON) 0.82 (OIN) 0.4 (rest)
σ_E	Elasticity of substitution between fossil and non-fossil energy	0.3
σ_I	Elasticity of substitution between physical investments and non-physical capital	0.3
σ_N	Elasticity of substitution between investments in R&D and research labor	0.3
σ_C	Elasticity of substitution between energy and non-energy goods in consumption	0.5
σ_W	Inter-temporal elasticity of substitution in the welfare function	0.6
$\sigma_{A,i}$	Armington elasticities	3.2 (AGR) 4.6 (MAS) 3.8 (EGY, OIN) 2.9 (rest)
σ_T	Elasticity of transformation	1

where: Agriculture (AGR), Refined Oil Products (OIL), Chemical Industry (CHM), Machinery and Equipment (MCH), Energy (EGY), Construction (CON), Transport (TRN), Banking and Financial Services (BNK), Insurances (INS), Health (HEA), Other Services (OSE), Other Industries (OIN)

Table 1

8 Figures

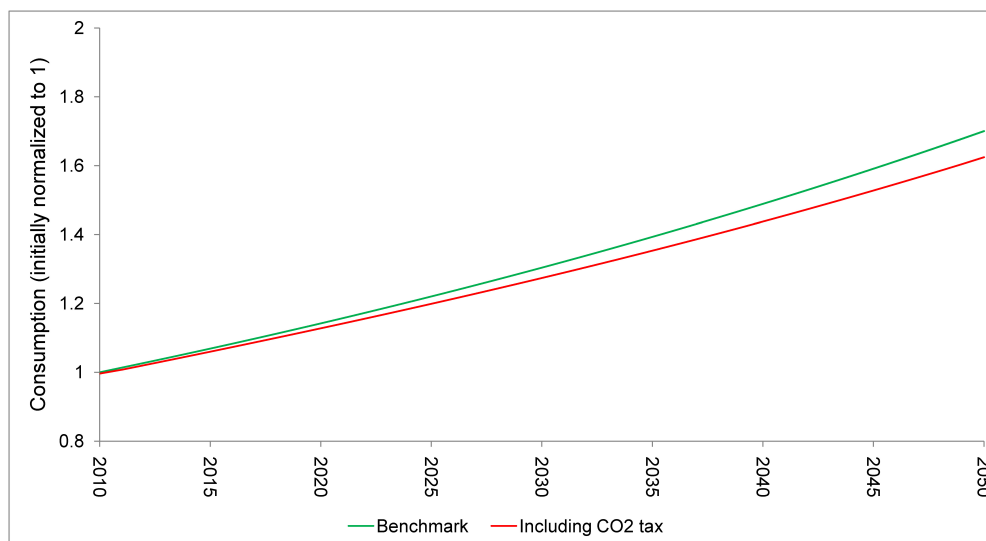


Figure 1: Consumption.

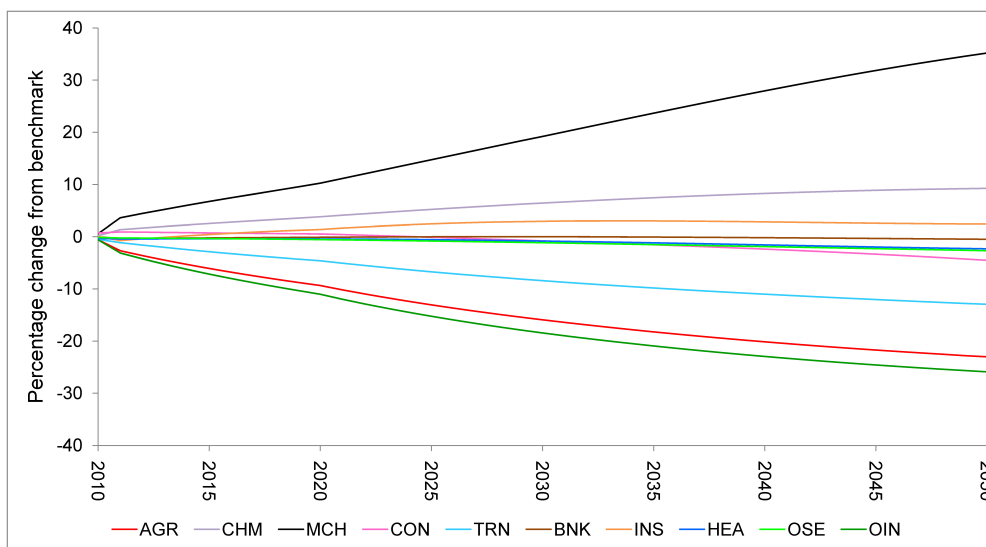


Figure 2: Sectoral output.

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