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Economics of endogenous technical change in CGE models -The role of gains from specialization

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Abstract

Computable general equilibrium models simulate the reaction of industries on carbon taxes. Their results differ strongly on the assumption of the underlying technologies. This paper compares two models and emphasizes the differences between their approaches to technology. The first model is the CITE model, which is the first model with endogenous growth based on gains from specialization so that growth dynamics result from investment incentives. The second model is a model with exogenous growth of endowments, which is the basis for many other CGE models. The results show that the CITE model unveils dynamics that cannot be obtained with the model based on exogenous growth. Reactions are stronger in the CITE model and industries need more time to approach the new balanced growth path.

Keywords: Endogenous growth, gains from specialization, CGE models, energy policy

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

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1 Introduction

A major task in the next decades for economies worldwide will be to decrease total emissions of greenhouse gases (GHG) and hence the carbon intensity of production. Energy efficiency must be strongly increased within the next years since a significant part of carbon dioxide emissions from the usage of energy. Public policies that target the reduction of total energy play a central role. In order to estimate the consequences of these political measures, one approach are computable general equilibrium (CGE) models. Their results depend on the assumptions for technical change and its industrial-specific effects (Buonanno et al (2003)).

The aim of this paper is to compare two approaches to model induced technical change and to emphasize the differences between two computable general equilibrium (CGE) models: the CITE model (based on endogenous growth dynamics and heterogeneous capital) and a model with homogenous capital and exogenous growth (the HK model). We choose the HK model as it displays dynamics that are the basis for many other CGE models. The CITE model can be considered as the first model with endogenous technical change resulting from gains from specialization. These gains yield incentives in the economy to grow fully endogenous without the assumption of exogenous growth rates of endowments. They are assumed to be the driver for growth both in the benchmark case without political measures as well as in policy scenarios.

The models yield different reactions of industries in three dimensions: In the CITE model, first, sectors show stronger reactions to the carbon tax and, second, the industries need a longer time frame to approach a new balanced growth path. Third, sectoral responses are distinct in the models so that the relative importance of the industries on the new balanced growth path varies.

The first CGE models were based on the assumption of exogenous growth of endowments and the autonomous amelioration of energy efficiency, such as Manne & Richels (1992), Nordhaus (1992), Peck & Teisberg (1992), Jorgenson & Wilcoxen (1993), and Nordhaus & Yang (1996). They ignored interconnections between technological change and policy measures. Changes in energy prices due to political actions only resulted in substitution of other factors for energy, leaving the rate of growth in energy efficiency unchanged. As energy policies have yet an impact on the price of fuels and therefore on the incentives to invest in research and development (R&D), they are strongly linked to technological change. Such policies might cause research efforts to concentrate on the discovery of new production methods or of entirely new products that depend less on energy. Moreover, energy policies can influence the accumulation of knowledge via learning-by-doing (LbD) related to experience with alternative energy fuels or energy-conserving processes. The inclusion of endogenous growth mechanisms leads to an increase of intertemporal connections and therefore stronger connects the cost of emission reduction in the future and measures taken today (Goulder & Mathai (2000), Boyd & Uri (1991), Dasgupta & Heal (1974)).

Newer CGE models also introduce elements of endogenous technological change, such as research and learning-by-doing. They incorporate insights from growth research since the seminal work of Solow (1956) and see technology as main driver of innovation and growth (Niosi (2008)). Examples are Messner (1997), Goulder & Schneider (1999), Goulder & Mathai (2000), Buonanno et al. (2001), Nordhaus (2002), van der Zwaan et al. (2002), Gerlagh et al. (2004), Popp (2004), and Gerlagh (2007). However, not all of these models include endogenous growth mechanisms also in the benchmark, meaning that the benchmark is still only defined by an exogenous growth rate. Additionally, these growth assumptions differ crucially from the endogenous growth dynamics of the CITE model, which are based on gains from specialization in production.

2 Growth from gains of specialization

New growth theory is based on the observation that technological innovation is an economic activity. Profit-maximizing agents optimize their behavior according to profit incentives. Endogenous growth theory thus builds on innovation theory that states that Schumpeterian profit incentives account for a major source of technological change (Weyant & Olavson (1999), Löschel (2002)). One possibility to endogenize growth dynamics according to new growth theory is to assume gains from specialization, either in consumption or production. This explanation is also used in the CITE model. It yields a new approach to include endogenous growth in CGE models. One of the major gains from this way to model growth is that both the benchmark as well as the counterfactuals are based on endogenous decisions to accumulate capital and thereby to increase productivity of the economy. The growth assumptions in the model are independent of exogenous growth assumptions for endowments.

Different authors along the centuries referred to gains from specialization. By observing the production in a pin factory, Smith already reported as early as in 1776 that specialization immensely increases the efficiency of the workers and therefore contributes to an augmented output. The increase of specialization led larger firms to have a higher output per worker and lower average cost per pin than a small pin factory.

The first attempt to include these gains from specialization in economic models was done by Spence (1976). He modeled consumer preferences that were enhanced if the amount of consumer goods rose. Dixit and Stiglitz (1977) and Grossman & Helpman (1991) refined Spence's approach. The first to combine specialization with production was Ethier (1982), who assumed that an increasing number of inputs to production would raise output (Barro & Sala-i-Martin (2004). Romer (1987,1990) followed Ethier (1982) and assumed that output is an increasing function of intermediate goods. The incentive to specialize or to invent new products in these models is always the existence of monopolistic power and therefore the possibility for an inventor to make profit with a new variety.

The empirical extent of specialization in the European Union has been estimated by Mangàni (2007), who analyzes the correlation of economic (in terms of GDP) and technological (i.e., R&D aggregate expenditure or the number of patents granted) sizes. She asserts a positive correlation between both. She distinguishes two technological dimensions: the intensity of technological activities (intensive margin) and their variety (extensive margin). The technological variety is hereby defined as the number of technological fields in which a country is active. Both dimensions are positively correlated with the country size, i.e., larger countries have a wider spectrum of technological fields and show a larger number of patents in each technological field. In Mangàni's estimation, technological variety accounts for about 40 % of the difference in patent application between larger and smaller economies and is therefore extremely important in explaining the different technological standards.

Many other empirical studies exist on gains from specialization in relation to trade. These models analyze the impact of specialization in exportation and importation of the productivity of the involved countries. Most of the papers find a close connection between technological innovation (meaning the growth possibilities) and export specialization patterns (Mangàni (2007)). Hummels and Klenow (2005) are close to Mangàni (2007)'s results and who find that the variety of goods accounts for about 60 % of the greater exports of larger economies. They also find that a distinctive correlation between the size of an economy and the degree of specialization exists. Their results are in line with other papers, such as Hummels et al. (2001) and Furman et al. (2002).

3 Structure of the models

The two models that are compared in this paper are the CITE model based on endogenous growth dynamics and heterogeneous capital and the HK model, a model with homogenous capital and exogenous growth. Both models have a decentralized structure, and each contains a Ramsey optimizer that maximizes utility by deciding about the extent of investments in different time periods. Therefore, the savings rate is endogenous in the two models. Both models represent open economies with trade modeled with Armington goods. The principal production structures are identical.

The main difference is in the inclusion of gains from specialization and therefore of heterogeneous capital in the CITE model. The incentives to accumulate capital generate endogenous growth dynamics. In comparison, in the model with homogenous capital, growth is assumed to come from endowments that grow by an exogenously defined rate in each period. This growth comes at no cost ("manna from heaven").

The policy scenario is based on a carbon tax that is relative to the carbon intensity of the output of the oil sector and of imported gas. The tax on gas amounts to 8 % of the price in the first period and then the absolute value remains constant over time. As oil contains 34 % more carbon than gas, the tax is initially 10.72 % and then stays constant. The revenues from the tax are redistributed with a subsidy on R&D that goes to all sectors except the oil sector. The amount that is distributed to each sector is optimized during the simulations.

In the theoretical calculations in this chapter we abstract from Armington goods to keep the analysis as simple as possible.

3.1 Final output

The production of final output is nearly identical in both models. The production of regular goods as well as final goods in the oil and in the energy sector have the same production structure. The main difference here is attributed to the intermediate goods. In the model with homogenous capital, intermediate goods enter the production of final goods directly, whereas in the CITE model, the intermediate goods are first combined to an intermediate composite (cf. Chapter 3.2) and then enter the production of the final good.

Starting with the CITE model, output of regular goods Y_n are produced using a sector specific intermediate composite Q_n and the final goods of all regular sectors n' that go to sector n, $Y_{n'n,t}$.

$$Y_{n,t} = \left[\alpha_{X,n} Q_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1-\alpha_{X,n}) \left(\min_{n' \in N} \left(\frac{Y_{n'n,t}}{y_{n'n}} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}} \tag{1}$$

The production functions for energy goods and oil goods resemble the production function above. In the production of energy goods, the above shown production structure is additionally combined with a Cobb-Douglas function of imported gas and the final good of the oil sector.

$$Y_{e,t} = \left[\alpha_{TFF} \left(GAS_t^{\alpha_{FF,gas}} Y_{o,t}^{\alpha_{FF,o}} \right)^{\frac{\sigma_E-1}{\sigma E}} + (1-\alpha_{tff}) B_{e,t}^{\frac{\sigma_E-1}{\sigma E}} \right]^{\frac{\sigma_E}{\sigma_E-1}} \tag{2}$$

$$B_{e,t} = \left[\alpha_{X,e} Q_{e,t}^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} + (1-\alpha_{X,e}) \left(\min_{n \in N} \left(\frac{Y_{ne,t}}{y_{ne}} \right) \right)^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} \right]^{\frac{\sigma_{Y,e}}{\sigma_{Y,e}-1}} \tag{3}$$

The production in the oil sector also resembles the production of regular goods, and it uses as additional input crude oil, which is added with a Leontief function.

$$Y_{o,t} = \min \left(\frac{CRU_t}{y_{cru}}, \frac{B_{o,t}}{y_{noncru}} \right) \tag{4}$$

$$B_{o,t} = \left[\alpha_{X,o} Q_{o,t}^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} + (1-\alpha_{X,o}) \left(\min_{n \in N} \left(\frac{Y_{no,t}}{y_{no}} \right) \right)^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} \right]^{\frac{\sigma_{Y,o}}{\sigma_{Y,o}-1}} \tag{5}$$

In comparison, in the HK model, no intermediate good composite exists as gains from specialization are completely absent. As a result, it is abstracted from a number of different intermediate goods but assumed that only one intermediate good per sector, $\tilde{X}_i$, exists. Consequently, instead of an intermediate composite, the intermediate goods $\tilde{X}_i$ enter the production functions of the sectors. The production function of regular goods then changes to

$$\tilde{Y}_{n,t} = \left[\alpha_{X,n} \tilde{X}_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1-\alpha_{X,n}) \left(\min_{n' \in N} \left(\frac{\tilde{Y}_{n'n,t}}{y_{n'n}} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}} \tag{6}$$

We choose to display variables that are distinct in the HK model compared to corresponding variable in the CITE model with an tilde. The production of energy goods equals

$$\tilde{Y}_{e,t} = \left[\alpha_{TFF}\left(GAS_t^{\alpha_{FF,gas}} Y_{o,t}^{\alpha_{FF,o}}\right)^{\frac{\sigma_E - 1}{\sigma E}} + (1 - \alpha_{tff})\tilde{B}_{e,t}^{\frac{\sigma_E - 1}{\sigma E}}\right]^{\frac{\sigma_E}{\sigma_E - 1}} \tag{7}$$

$$\tilde{B}_{e,t} = \left[\alpha_{X,e}\tilde{X}_{e,t}^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} + (1 - \alpha_{X,e})\left(\min_{n \in N}\left(\frac{\tilde{Y}_{ne,t}}{y_{ne}}\right)\right)^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}}\right]^{\frac{\sigma_{Y,e}}{\sigma_{Y,e}-1}} \tag{8}$$

The production of oil in the HK model corresponds to

$$\tilde{Y}_{o,t} = \min\left(\frac{CRU_t}{y_{cru}}, \frac{\tilde{B}_{o,t}}{y_{noncru}}\right) \tag{9}$$

$$\tilde{B}_{o,t} = \left[\alpha_{X,o}\tilde{X}_{o,t}^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} + (1 - \alpha_{X,o})\left(\min_{n \in N}\left(\frac{\tilde{Y}_{no,t}}{y_{no}}\right)\right)^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}}\right]^{\frac{\sigma_{Y,o}}{\sigma_{Y,o}-1}} \tag{10}$$

3.2 Intermediate good composite and intermediate good

This chapter illustrates the main differences in both models. As already explained above, the intermediate goods are combined in the CITE model to an intermediate composite, whereas in the HK model the intermediate good directly enters the production function of the final good. In this chapter the aggregation to the intermediate composite in the CITE model as well as the resulting differences for the optimization problems of the intermediate good producers are explained.

In the CITE model, the intermediate good composite Q_i is produced from a number of different intermediate goods x_{ij}. The amount of intermediate goods is assumed to equal the capital stock in each sector.

$$Q_{i,t} = \left[\sum_{j=1}^{K_{i,t}} x_{ij,t}^{\kappa}\right]^{\frac{1}{\kappa}} \tag{11}$$

As all intermediate goods x_{ij} are produced symmetrically with the same production structure, we can assume $x_{ij} = x_i$ and the above production function can be rewritten as

$$Q_{i,t} = K_{i,t}^{\frac{1}{\kappa}} x_{i,t} = K_{i,t}^{\frac{1-\kappa}{\kappa}} X_{i,t} \tag{12}$$

with

$$X_i = K_i x_i \tag{13}$$

The intermediate goods are assumed to be produced with labor, L_{ij}, policy invariant capital, VK_{ij}, and energy, Y_e. Policy invariant capital is introduced for reasons of calibration and refers to the share of capital from the input-output-table that is not part of the capital stock that can be accumulated by investments (cf. Chapter 4).

$$x_{ij,t} = \left[\alpha_{L,i} L_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1 - \alpha_{L,i} - \alpha_{VK,i}) Y_{ex_{ij},t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} \right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}} \tag{14}$$

The optimization of each x_{ij} producer yields the inverse demand functions

$$\frac{1}{\kappa} w_t = \alpha_{L,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{L_{ij,t}} \right)^{\frac{1}{\sigma_X}} \tag{15}$$

$$\frac{1}{\kappa} p_{VK,t} = \alpha_{VK,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{VK_{ij,t}} \right)^{\frac{1}{\sigma_X}} \tag{16}$$

$$\frac{1}{\kappa} p_{Y_e,t} = (1 - \alpha_{L,i} - \alpha_{VK,i}) p_{x_{ij},t} \left(\frac{x_{ij,t}}{Y_{ex_{ij},t}} \right)^{\frac{1}{\sigma_X}} \tag{17}$$

where $\frac{1}{\kappa}$ denotes the markup over marginal costs. It is important to note here that each x_{ij} has a constant quantity of production over time. Thus, the growth index of x_{ij} equals one.

In comparison, the HK model includes only one intermediate good per sector, $\tilde{X}_i$, which grows at the rate of its inputs. Of these inputs, the growth rates of VK_i and L_i are exogenously given. Therefore, all growth dynamics depend on the growth rates of these inputs. The production function for the intermediate good is given as

$$\tilde{X}_{i,t} = \left[\alpha_{L,i} L_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{K,i} K_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1 - \alpha_{L,i} - \alpha_{VK,i} - \alpha_{K,i}) Y_{e\tilde{X}_i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} \right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}} \tag{18}$$

The intermediate good $\tilde{X}_i$ of the HK model is comparable to X_i in the CITE model. However, there exist some crucial differences. First of all, capital is used directly in the production function of $\tilde{X}_i$. Second, the total amount of $L_{i,t}$, $VK_{i,t}$, and $Y_{e\tilde{X}_i,t}$ in the HK model must equal the sum of each used by the intermediate good producers in the CITE model in the first period:

$$L_{i,0} = \sum_j L_{ij,0} \tag{19}$$

$$VK_{i,0} = \sum_j VK_{ij,0} \tag{20}$$

$$Y_{e\tilde{X}_i,0} = \sum_j Y_{ex_{ij},0} \tag{21}$$

The most important distinction between $\tilde{X}_i$ and X_i can be found in the dynamics. These are different as the inputs in the HK model exogenously grow over time whereas they remain constant in the CITE model.

The maximization problem for the intermediate good producer in the HK model is

$$\max_{L_{i,t}, VK_{i,t}, K_{i,t}, Y_{e\tilde{X}_i,t}} p_{\tilde{X}_i,t}\tilde{X}_{i,t} - w_t L_{i,t} - p_{VK,t} VK_{i,t} - p_{K,t} K_{i,t} - p_{Y_e,t} Y_{e\tilde{X}_i,t} \tag{22}$$

s.t. (18). The resulting inverse demand functions are

$$w_t = \alpha_{L,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{L_{i,t}} \right)^{\frac{1}{\sigma_X}} \tag{23}$$

$$p_{VK,t} = \alpha_{VK,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{VK_{i,t}} \right)^{\frac{1}{\sigma_X}} \tag{24}$$

$$p_{K,t} = \alpha_{K,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{K_{i,t}} \right)^{\frac{1}{\sigma_X}} \tag{25}$$

$$p_{Y_e,t} = (1 - \alpha_{L,i} - \alpha_{VK,i}) p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{Y_{e\tilde{X}_i,t}} \right)^{\frac{1}{\sigma_X}} \tag{26}$$

Comparing the FOCs of the intermediate producer(s) in both models, it is striking that in the CITE model, each intermediate good producer can charge a mark-up on the marginal costs. As in the HK model we assume competitive markets, prices always equal marginal costs.

3.3 Capital accumulation

Capital accumulation in the basis of growth dynamics in the CITE model. Intermediate firms conduct research and development and thereby invest in a capital stock composite. Intermediate firms j invest in two types of capital, in physical capital ($I_{P_{ij}}$) and in non-physical capital ($I_{NP_{ij}}$). Both types of investment can only be effected intra-sectoral, i.e. investments in new capital is sector-specific. Non-physical capital is produced by investments in R&D, $I_{R\&D,ij}$, and labor in research, RL_{ij}. The formulation of $I_{R\&D,ij}$ stems from the fact that we apply data for R&D investments from the Swiss input-output-table for $I_{R\&D,ij}$. It should not be confused with R&D as an activity that we refer to in the production process. In the HK model, capital is accumulated in the same manner, but it is used only as factor in production and not as driver for growth.

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

Together with investments in physical capital, $I_{P,ij}$, non-physical capital is then used in the production of a capital composite K_{ij}.

$$K_{ij,t+1} = \left[\gamma_i I_{P_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}\right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} + (1-\delta) K_{ij,t} \qquad (27)$$

δ depicts the depreciation rate of capital. Consequently, the increase of capital per sector is equal to

$$K_{i,t+1} - K_{i,t} = \triangle\, K_{i,t+1} = \left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}\right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} - \delta K_{i,t} \qquad (28)$$

This relation implies several aggregations. First, investments in physical capital and in R&D of the j producers of intermediate goods in each sector i can be added up to investments of the sector in physical and non-physical capital and in R&D according to

$$I_{P_i,t} = \sum_{j=1}^{K_{i,t}} I_{P_{ij},t}$$

$$I_{NP_i,t} = \sum_{j=1}^{K_{i,t}} I_{NP_{ij},t}$$

$$I_{R\&D_i,t} = \sum_{j=1}^{K_{i,t}} I_{R\&D_{ij},t}$$

The same must hold for the capital composite K_i, assuming $K_{ij,t} = 1$:

$$K_{i,t} = \sum_{j=1}^{K_{i,t}} K_{ij,t}$$

In the HK model, the above investment equations apply as well with the aggregated values above, i.e., investments in capital are done on a sectoral level only.

In the CITE model, intermediate firms need to finance their research activities in advance. More specifically, labor and investments that are necessary to invent a new intermediate good for period $t+1$ need to be paid in period t. To be able to do so, intermediate firms borrow $p_{K,t}I_{ij,t}$ from the representative household:

$$p_{K,t}I_{ij,t} = w_{R,t}RL_{ij,t} + p_{A_i,t}(I_{P_{ij},t} + I_{R\&D_{ij},t})$$

After the discovery of a new blueprint they re-pay the household the remaining profits from the production of the intermediate.

3.4 Consumption

The intertemporal allocation of factors is optimized in both models by a representative household that maximizes utility having perfect foresight. Utility U is drawn from a consumption good C and is discounted at the rate ρ over time. The utility function of the household is identical in the models:

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\theta} - 1}{1-\theta} \tag{29}$$

Consumption consists of two goods, energy Y_{ec} and a final good composite C_S that is composed of the final goods of the regular sectors.

$$C_t = \left[(1-\beta)C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta Y_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C - 1}} \tag{30}$$

$$C_{S,t} = \prod_{n \in N} Y_{nc,t}^{\beta_{NE,n}} \tag{31}$$

Hereby, Y_{nC} denotes the part of the final output of sector n that is used for consumption. $\beta_{NE,n}$ is the value share of final good n in the composite $C_{S,t}$ and the sum of these shares, $\sum\limits_{n \in N} \beta_{NE,n}$, adds up to one to assume constant returns to scale. The budget constraint of the household in both models equals

$$\begin{aligned} p_{V,t+1}V_{t+1} = & (1 + r_{t+1})p_{V,t}V_t + w_t L_t + w_{R,t} RL_t + p_{VK,t} VK_t \\ & - p_{Y_e,t} Y_{ec,t} - \sum_{n \in N} p_{Y_n,t} Y_{nc,t} - \sum_{i \in I} p_{V,t} I_{i,t} \end{aligned} \tag{32}$$

The household is able to hold assets V on the capital market, which includes that total investments made by the household must equal investments in physical and in non-physical capital, $I_{i,t} = I_{P_i,t} + I_{NP_i,t}$. Energy is assumed to be an endowment of the household, and therefore income from energy goes to the consumer.

4 Calibration of the models

The models are calibrated according to the input-output-table 2005 of the Swiss economy. The latter provides information about the intermediate demands as well as the sectoral share in investments and consumption. Additionally, labor and capital as inputs to production are displayed.

This chapter gives some information about the calibration of the CITE model and of the HK model with which it is compared.

The capital stocks of the CITE model and of the HK model are calibrated by dividing the capital stock form the input-output-table in two parts. The definition of capital is based upon the assumption that the size of the capital stock has a significant influence on the growth rate in the CITE model. The policy invariant capital is the difference between the calibrated capital stock and the capital stock from the input-output-table.

For the comparison of the relations in Table 1, it must be taken into account that X_i is defined differently in the CITE model than in the HK model. In the CITE model, X_i is produced using labor, energy, and policy invariant capital. The capital stock is needed exclusively as a precondition to produce X_i and is thus not included in the calculation of X_i from the input-output-table. On the contrary, in the HK model, capital is a direct input to the production of the intermediate good and is therefore also included in the calculation of the intermediate good. This difference in the definitions is essential for the interpretation of the capital, energy, and labor shares.

		AGR	**OIL**	**CHM**	**MCH**	**EGY**	**CON**
E/Y		0.04	0.00	0.01	0.01	0.38	0.02
E/X	CITE	0.10	0.04	0.04	0.03	0.82	0.05
E/X	NK	0.08	0.03	0.03	0.02	0.62	0.04
X/Y	CITE	0.36	0.06	0.32	0.28	0.47	0.38
X/Y	NK	0.48	0.09	0.42	0.37	0.62	0.51
K/Y	CITE & NK	0.12	0.02	0.11	0.09	0.16	0.13
VK/Y	CITE & NK	0.16	0.03	0.17	0.02	0.04	0.01
L/X	CITE	0.46	0.44	0.44	0.89	0.10	0.94
L/X	NK	0.35	0.33	0.33	0.67	0.08	0.70

		TRN	**BNK**	**INS**	**HEA**	**OSE**	**OIN**
E/Y		0.05	0.00	0.00	0.01	0.01	0.03
E/X	CITE	0.13	0.01	0.01	0.02	0.03	0.08
E/X	NK	0.10	0.00	0.01	0.02	0.02	0.06
X/Y	CITE	0.35	0.50	0.28	0.54	0.49	0.30
X/Y	NK	0.47	0.67	0.38	0.72	0.65	0.40
K/Y	CITE & NK	0.12	0.17	0.09	0.18	0.16	0.10
VK/Y	CITE & NK	0.03	0.12	0.06	0.01	0.09	0.03
L/X	CITE	0.79	0.75	0.79	0.96	0.78	0.83
L/X	NK	0.59	0.56	0.60	0.72	0.59	0.62

Table 1: Relations in the calibration of the models

5 Dynamics of the CITE and the HK growth model

The dynamics of the CITE model are based on gains from specialization that rise with an increasing capital stock. This chapter compares these dynamics with those of a HK model with exogenous growth. The capital stock of this model is calibrated identically to that of the CITE model to ensure that the differences in the dynamics arise only from the general growth dynamics and not from the quantitatively difference of the capital stocks. The center of interest is to understand the effects of the different investment incentives on intertemporal dynamics and structural change.

5.1 Effects on production, capital, and consumption

After the introduction of a carbon tax, all sectors in the economy must adjust to the new situation. The tax increases the prices of the fossil fuels, which directly affects production and investments.

The reaction of final output in the CITE model differ considerably from those in the HK model in three aspects (cf. Figures 1 and 2). First of all, the effects of the tax are in most sectors very small in the HK model as their production changes only less than 1 % compared to the benchmark case. Only the energy and the oil sector show a strong reduction in output (4.3 and 6.2 %, respectively). On the contrary, in the CITE model most of the sectors react in a more pronounced way, which leads to a larger spread in the figure. The production of the energy and the oil sector decrease even more, whereas the machinery sector gains and increases its production by 2.6 % in the last period. This positive reaction is at least partly ascribable to the small energy share of the machinery sector. The direct effects of the carbon tax are hence limited. Other sectors have large energy shares, such as the sectors agriculture and other industries and suffer more from the tax. Additionally, the machinery sector has a high elasticity of substitution between energy and the other inputs for the production of intermediate goods. The production of the agriculture industry decreases by 1.4 % and output of other industries drops by 1.7 %.

**** Figure 1 ****
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**** Figure 2 ****
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The second aspect in which both models differ is the speed in which the sectors approach a new balanced growth path after the introduction of a carbon tax. The adaptation lasts much longer in the CITE model than in the HK model, it even takes decades for the sectors to adjust to the new situation. In the HK model, all industries reach the new balanced growth path very fast and then remain there for the rest of the time horizon. This difference in the dynamics results from the fact that only labor and policy invariant capital can substitute for energy in the CITE model. This yields limited possibilities to adapt and the industries need to invest in capital to increase their productivity. The slow adjustment is due to the fact that capital accumulation takes time. In the HK model, capital can additionally and immediately substitute for energy, which results in a fast change of the composition of inputs to production. As a consequence, the level of production adjusts very quickly to the tax. On the other hand, capital cannot, like in the CITE model, enhance total productivity of the intermediate good.

The third main distinction of the models concerns the structural composition of the economy. The sectoral reactions to the carbon tax are different in the models, which yields different relations of the sizes of the industries. In the CITE model, the machinery and equipment sector is the industry that benefits most from the tax. This sector has a small energy share and also a relatively small share of capital in final output. Due to these conditions, the machinery sector can react very flexible to the tax. The impact on costs is very limited as energy costs are only a small fraction of total costs. Additionally, the small share of capital enables the sector to proportionately increase its capital share with relatively small investments. These investments, in turn, contribute to a higher productivity, which overcompensates the increase in energy prices. This mechanism is not possible in the HK model. Here, the machinery sector can only substitute capital for energy but cannot increase the total productivity of the intermediate good. As the elasticity of substitution is below 1, the possibility to use capital instead of energy is limited. As a result, the machinery sector does not increase production in the HK model as much as in the CITE model.

The consequences of the difference in the growth dynamics can also be seen in other sectors. The insurance industry, for example, decreases production initially in the CITE model and then intensifies production over time due to an increase of the capital stock. In the end of the time period, output is slightly above the benchmark level. In the HK model however, output rises directly after the introduction of the tax and remains high so that at the end of the time frame the insurance sector is the sector that has the largest rise of output.

As the development of production is tightly connected to the evolution of capital, all three above mentioned dissimilarities can also be seen there (cf. Figures 3 and 4). First, the spread of the capital stock is much larger in the CITE model. Second, the time until the capital stocks reach the new balanced growth path is longer in the CITE model. And finally, the structural composition of the sectoral capital stocks changes. Additionally to these effects, it is interesting to look at the evolution of the capital stock of the energy sector. In the HK model, the capital stock behaves similarly to the output. Both strongly decrease compared to the benchmark. In the CITE model, however, we can see that the capital stock is even higher in the new balanced growth path than in the benchmark. This observation shows again the difference in the investment incentives in both models.

**** Figure 3 ****
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**** Figure 4 ****
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The changing combination of inputs to production also has an influence on the demand for other inputs than capital, such as fossil fuels (cf. Figure 5). The imports of crude oil and gas decrease more in the CITE model than in the HK model. Crude oil drops in the CITE model by 1.4 % more than in the HK model over the time horizon. The difference in gas importation is smaller and about 0.6 %. The use of oil shows similar patterns and decreases by 0.8% more in the CITE model than in the HK model.

**** Figure 5 ****
about here

After the introduction of a carbon tax, the production structure of the economy changes in both models. Despite these changes, the negative consequences for consumption and welfare remain very limited (cf. Figures 6 and 7). Although consumption initially falls by around 0.40 and 0.16 % in the CITE and the HK model, respectively, it quickly recuperates and is only slightly below the benchmark level in the last period. Welfare is very similar in both models and decreases only slightly (less than 1 %) compared to the benchmark.

**** Figure 6 ****
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**** Figure 7 ****
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5.2 Effects on endowments

The consequences of a carbon tax for labor are structurally similar to output in both models (cf. Figures 8 and 9). The spread of demand for labor is larger in the CITE model than in the HK model. The demand in both models needs some time to adapt. although the CITE model shows a longer time period for adaption in most sectors (except for the chemical industry and the construction sector). The main difference compared to output is the behavior of the energy sector in the CITE model, which has a very high demand for labor.

**** Figure 8 ****
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**** Figure 9 ****
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Similarly to the demand for labor that almost duplicates the patterns of output, labor in research shows a similar behavior compared to the capital stock (cf. Figures 10 and 11). This result is very intuitive and at the same time gives some insight to the development of the labor market. Not only changes the proportion of labor between the sectors, also the intrasectoral relation of labor to labor in research changes compared to the benchmark.

**** Figure 10 ****
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**** Figure 11 ****
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The changes in demand are also reflected in the prices. If we regard the wage for labor in research in Figures 12 and 13, we find that it increases in both models, but it remains on a higher level in the CITE model. We can conclude that the marginal product of labor in research stays higher in the CITE model than in the HK model in the long run. This difference is also a consequence of the different roles of capital in the models. In both models, labor in research contributes to investments, which raise the capital stocks.

However, capital has a larger effect on production and therefore a larger marginal product in the CITE model as it increases overall productivity of the intermediate composite good. In the HK model, an increase in capital can only enhance production of intermediates by substitution and not by a productivity factor. It has therefore a smaller possibility to influence output. This fact is reflected in the wage of labor in research.

**** Figure 12 ****
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**** Figure 13 ****
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5.3 Effects on trade

Trade behaves very differently in both models. It increases by 3.6% in the CITE model and decreases by 0.2% in the HK model (net trade over the whole time horizon). This development reflects the sectoral trade structures that are different in both models. The machinery sector, for instance, increases net trade by 126% in the CITE model, whereas the same sector rises net trade only by 9% in the HK model. Although the machinery sector is only a small sector in the Swiss economy, other sectors show similar changes in trade behavior. The sector of other industries, OIN, has by far the largest total amount of net trade in Switzerland, and it rises its net trade by 5% in the CITE model. In comparison, the same sector increases net trade only by 1% in the HK model.

Similar to the differences in output behavior, the spread of net trade is larger in the CITE model than in the HK model. The transport sector shows a decrease in net trade of 7% in the CITE model and is the regular sector with the largest drop in trade. In the HK model, however, trade of the transport sector decreases only by 3%.

**** Figure 14 ****
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In the benchmark case, Switzerland is an exporter of energy. However, if the carbon tax is introduced, the energy production and the use of energy decline to a smaller extent than fossil fuel importation in both models (cf. Figure 14). As a result, Switzerland uses more of its own energy production and trade of energy drops strongly in both models. The CITE model shows a larger reaction because of the lower production and consumption patterns.

5.4 Sensitivity analysis

The influence of capital on the dynamics becomes clearer in both models if we regard reactions initiated by a change in two important elasticities. As capital goes in the HK model in the production of the intermediate good, the elasticity that connects $\tilde{K}_i$ with the other inputs in the production of $\tilde{X}_i$, $\sigma_{X,i}$, plays an important role. Moreover, the elasticity in the production of the final good that connects the intermediate good (the intermediate composite in the CITE model) and the inputs from other sectors, $\sigma_{Y,i}$ influences the outcomes. To find out how sensitive the models react to a change in the elasticities, we run the counterfactual with elasticities that are doubled.

The reactions of the models to elasticities changes are quite small and the models are hence very stable. The CITE model is slightly more reactive to changes than the HK model, which showed few effects of a doubling of the elasticities.

6 Conclusion

The comparison of the dynamics of the CITE model, based on endogenous growth, with a standard HK model, based on exogenous growth, shows different reactions to a carbon tax. These are based on the distinct investment incentives. In the CITE model, capital growth generates gains from specialization and ensures endogenous growth dynamics. A carbon tax changes incentives to that investments target at a substitution of energy in the production and result in a higher productivity of the intermediate composite. This, in turn, contributes to a change in the production of the final outputs. In the HK model, on the contrary, capital accumulation can only contribute to a substitution for energy but not to an increase of productivity. Accordingly, investment incentives are different compared to the CITE model.

For most industries, the CITE model shows a stronger sensitivity to the change in input costs than in the HK model. Mainly three differences occur: First, the spread of output of the sectors is larger in the CITE model. Second, the speed in which the industries approach a new balanced growth path is lower in the CITE model. And finally, the structural composition of the economy is different in the two models. It can therefore be concluded that the endogenous growth mechanism in the CITE model uncovers dynamics triggered by a carbon tax, which cannot be displayed with a HK model.

7 Literature

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8 Appendix

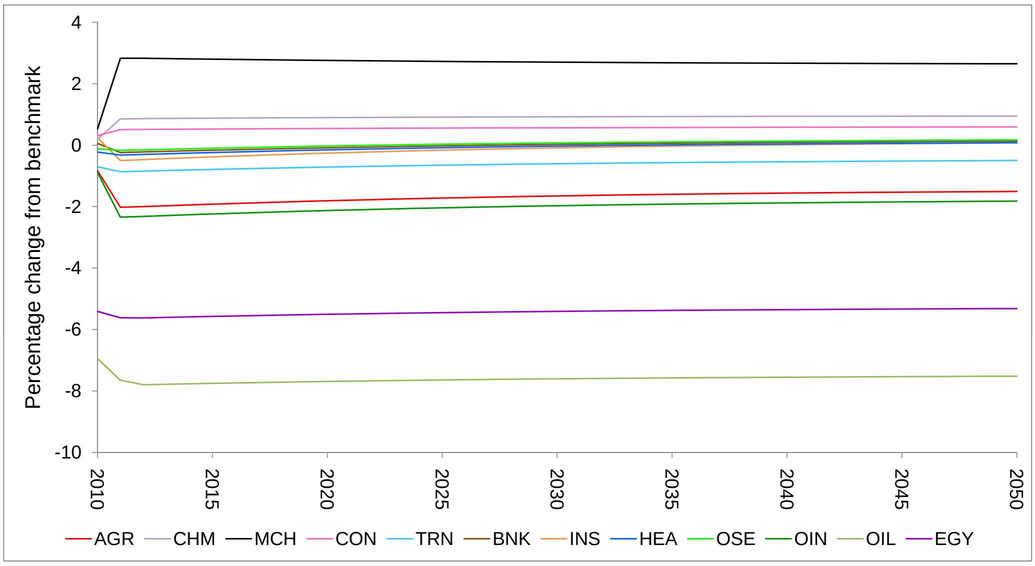

Figure 1: Sectoral outputs in the CITE model

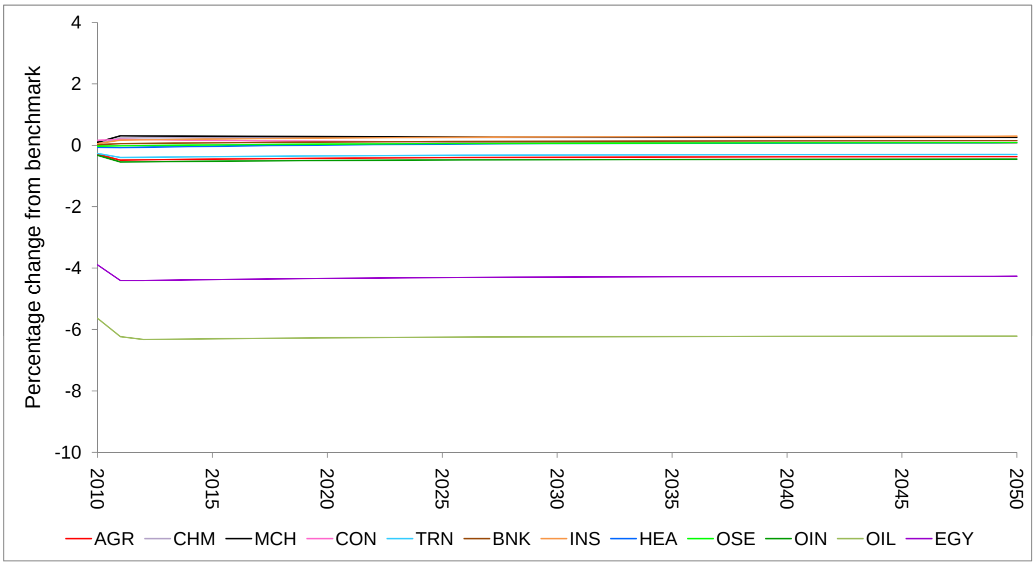

Figure 2: Sectoral outputs in the HK model

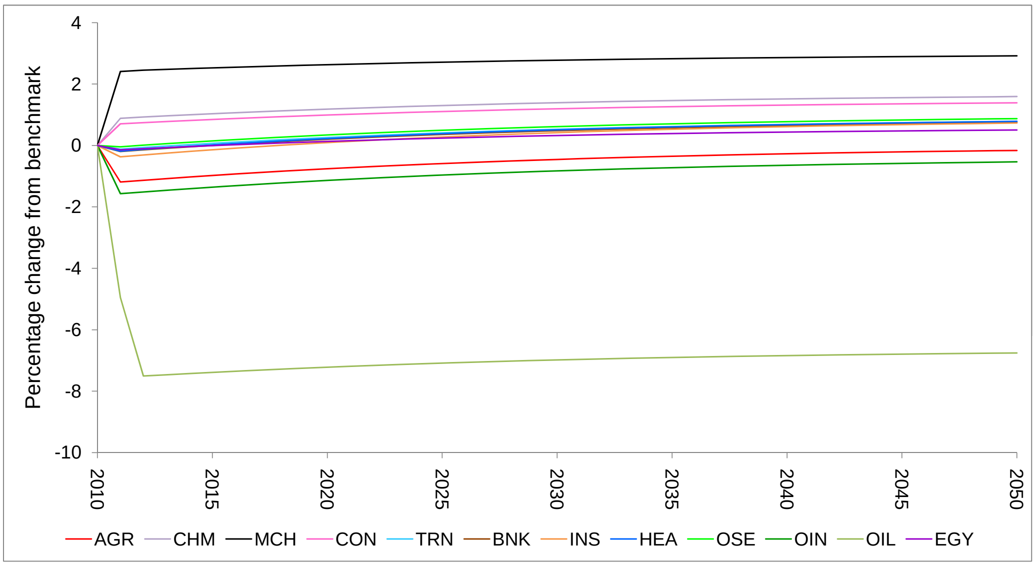

Figure 3: Sectoral capital stocks in the CITE model

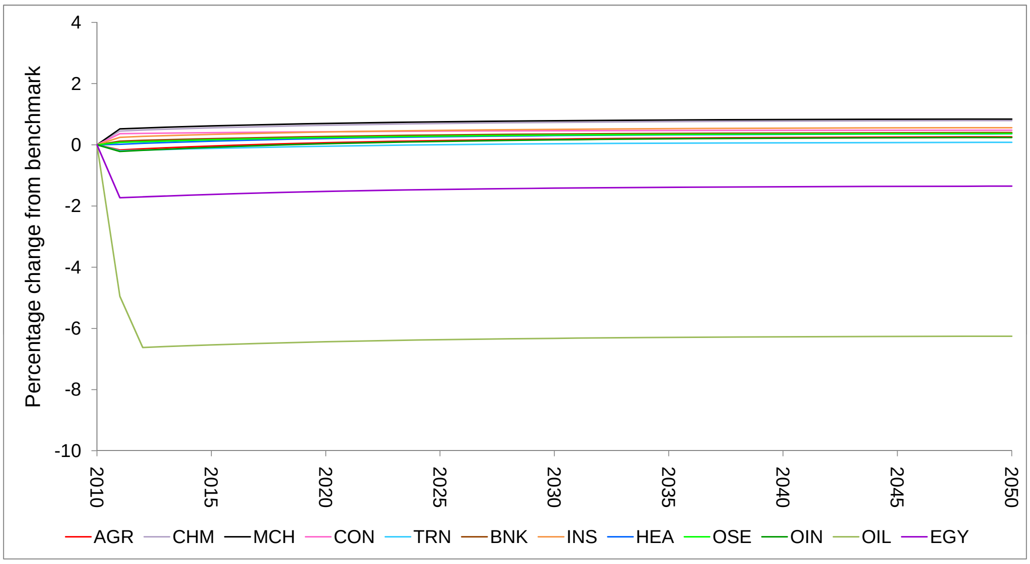

Figure 4: Sectoral capital stocks in the HK model

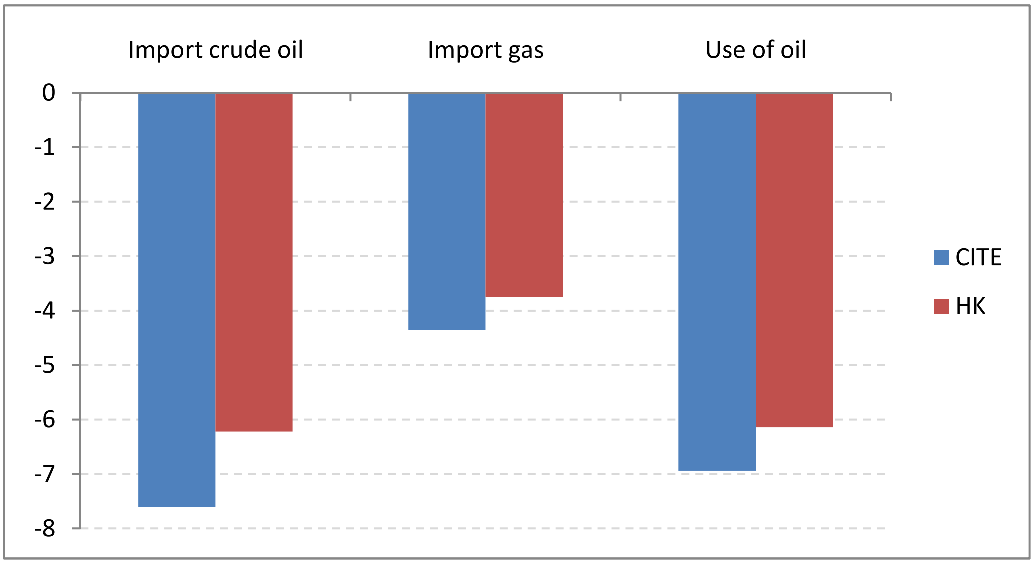

Figure 5: Fossil fuel importation

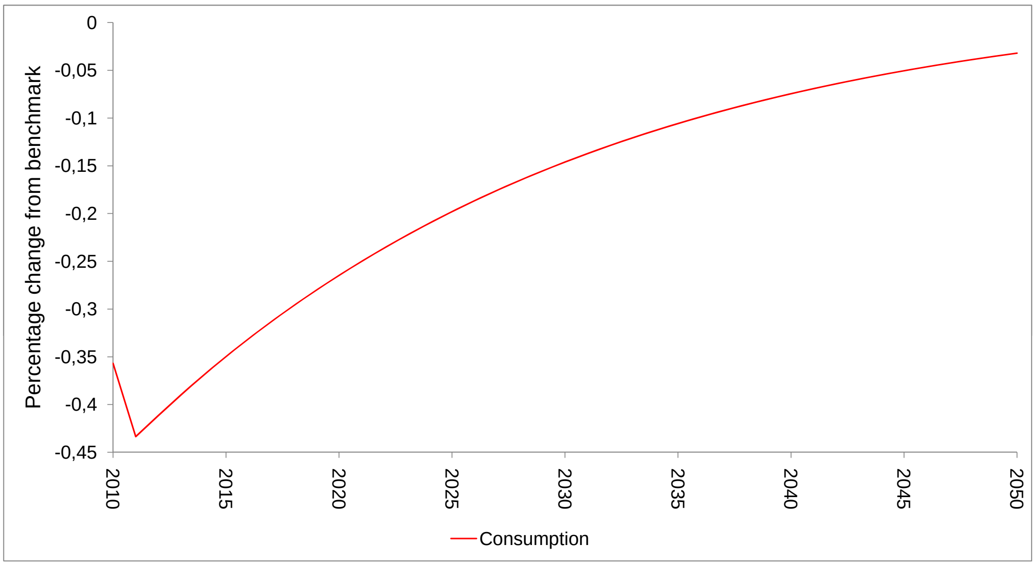

Figure 6: Consumption in the CITE model

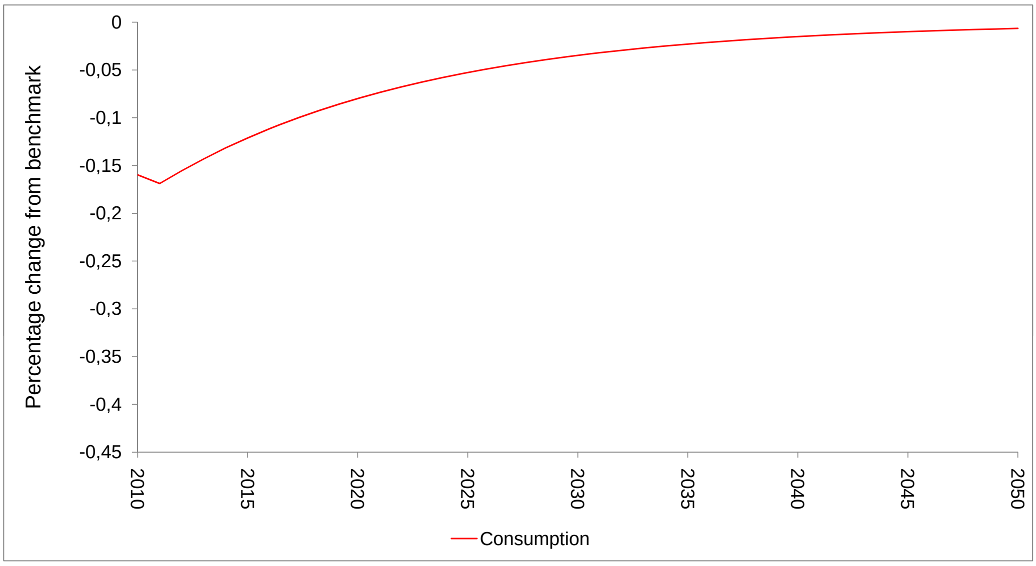

Figure 7: Consumption in the HK model

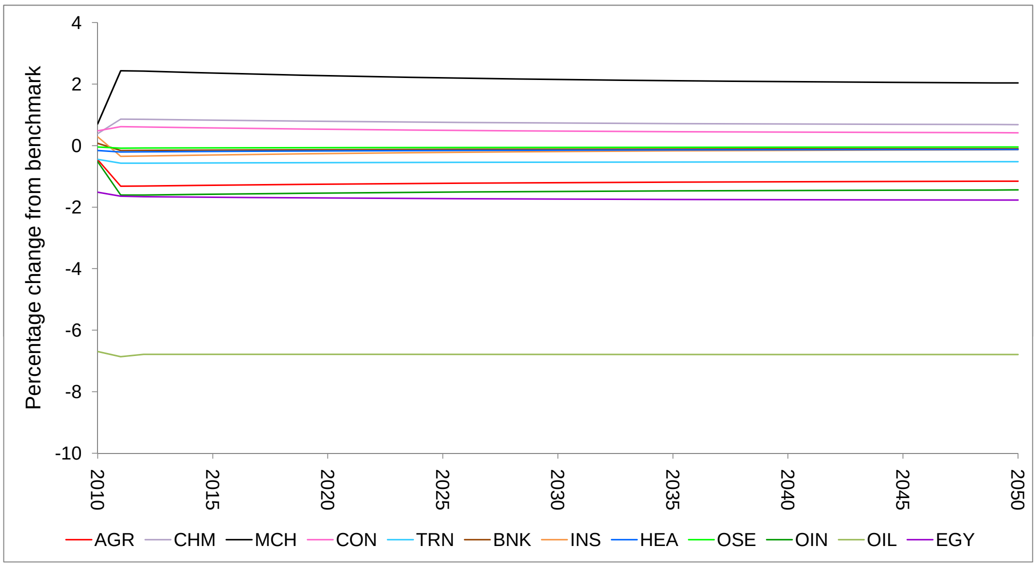

Figure 8: Labor demand in the CITE model

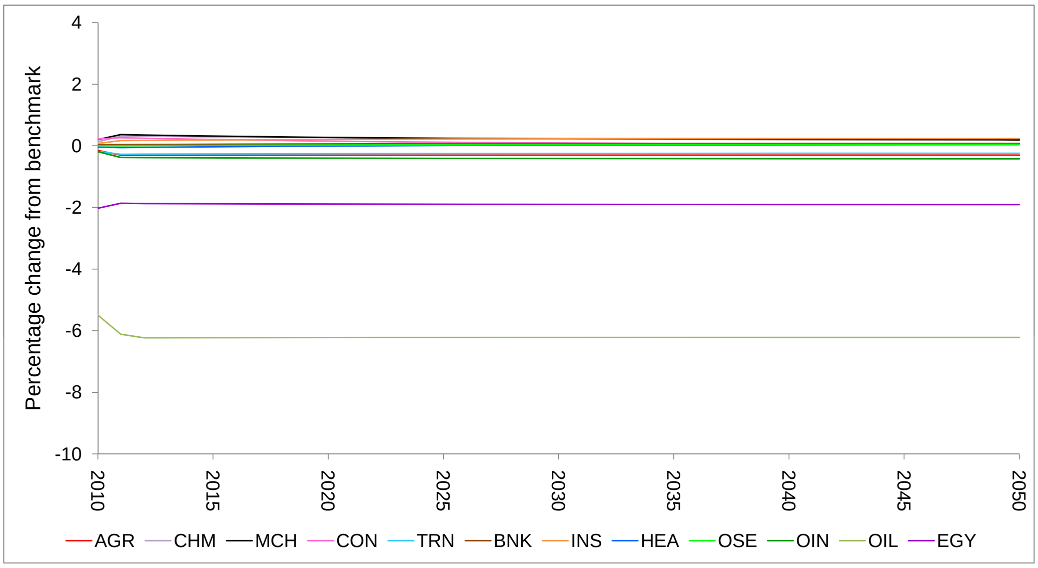

Figure 9: Labor demand in the HK model

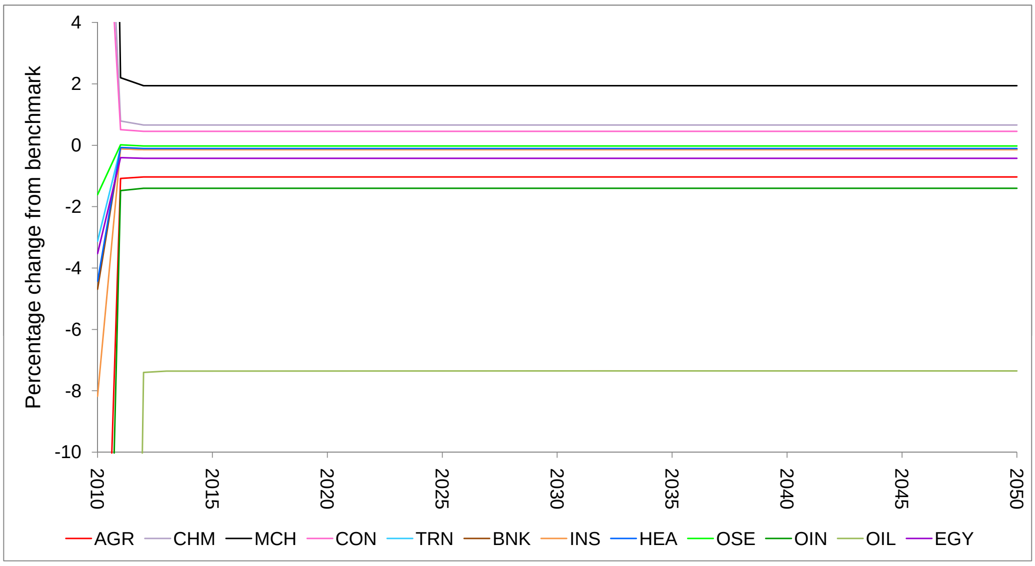

Figure 10: Demand for labor in research in the CITE model

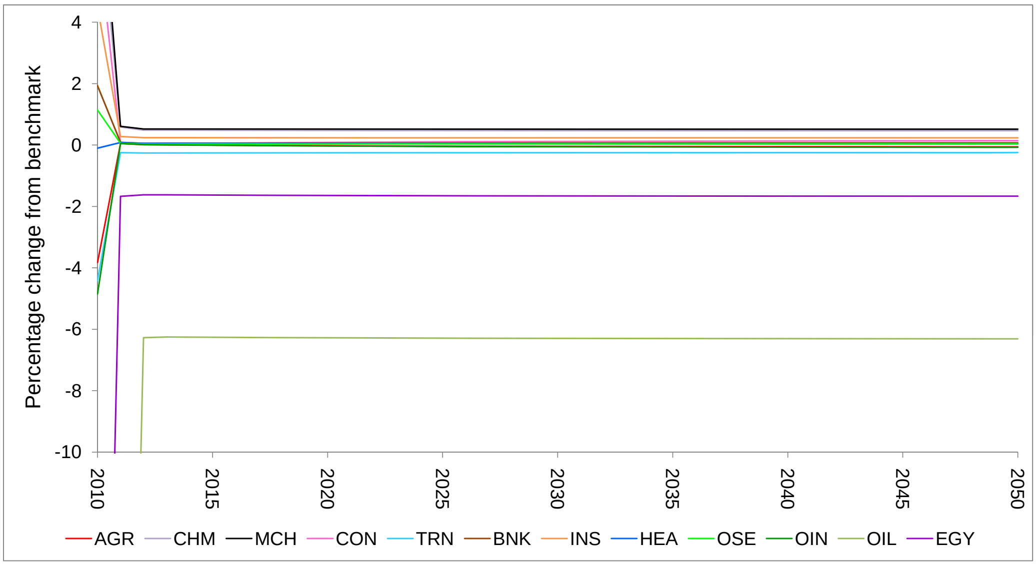

Figure 11: Demand for labor in research in the HK model

Figure 12: Marginal product of labor in research in the CITE model

Figure 13: Marginal product of labor in research in the HK model

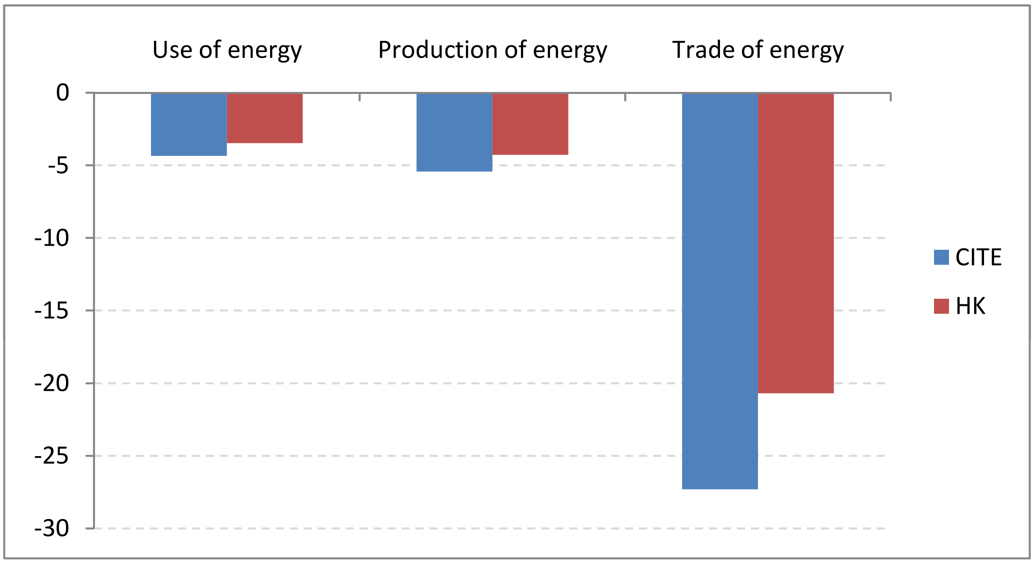

Figure 14: Use, production, and trade of energy

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