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Carbon policy in a high-growth economy: The case of China

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Abstract

There is widespread concern that an international agreement on stringent climate policies will not be reached because it would imply too high costs for fast growing economies like China. To quantify these costs we develop a general equilibrium model with fully endogenous growth. The framework includes disaggregated industrial and energy sectors, endogenous innovation, and sector-specific investments. We find that the implementation of Chinese government carbon policies until 2020 causes a welfare reduction of 0.3 percent. For the long run up to 2050 we show that welfare costs of internationally coordinated emission reduction targets lie between 3 and 8 percent. Assuming faster energy technology development, stronger induced innovation, and rising energy prices in the reference case reduces welfare losses significantly. We argue that increased urbanization raises the costs of carbon policies due to altered consumption patterns.

Keywords: Carbon policy; China; Endogenous growth; Induced innovation; Urbanization.

JEP Classification: Q54, O41, O53, C68

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1 Introduction

China has become the world's largest greenhouse gas emitter: it consumes around fifty percent of global coal extraction and generates eighty percent of its electricity with coal. At the same time, the economic growth of China has been unprecedentedly high, with an average annual growth rate of more than ten percent over the last twenty years.¹ Future climate policies are becoming one of the top priorities for Chinese policy makers as well as for the world community, which is seeking a new international climate agreement.²

From the perspective of applied macroeconomics, it seems rewarding to inquire into the dynamic impact of restricted input use in a high-growth economy and to derive results on the size of its effects. Notably, if climate policy requires stabilization of future carbon use, the growth rates of fossil fuel inputs in China will contrast sharply with past and current income growth rates, suggesting major welfare losses with climate policies. One may also argue that a successfully growing economy is powerful in achieving a new growth trajectory. The sky-high savings and investment rates and the associated productivity development may support the necessary transition. The nexus of energy and growth is the fundamental research issue in this field. We focus on the effects of carbon policy on the economic growth.

In this paper we develop a multi-sector endogenous growth framework, including energy inputs. We argue that the assessment of climate policies, specifically in a case like China, is only accurate when we capture economic growth in an appropriate way. We use the well-known increasing-division-of-labor framework developed by Romer (1990) as a theoretical foundation of our model. Here, endogenous innovation and capital investments increase the number of goods varieties and the stock of knowledge, which supports growth by raising productivity. We extend the original theoretical framework to a multi-sector approach with energy and foreign trade; growth of each economic sector is determined endogenously. We then

¹According to World Bank data, the average annual growth rate of China was 10.1% in the periods 1991-2001, 10.9% between 2001-2011.

²So far, China's position has been to offer emission intensity targets but no emission cuts; we will study the different targets and their effects in detail below. Furthermore, we notice that regional pilot cap-and-trade programs are now being implemented as part of the current Chinese climate policy. This signals that the Chinese government is making efforts for the absolute emission cuts.

use the framework as a basis for a computable general equilibrium model, i.e. we calibrate the model with Chinese input output data and study the macroeconomic effects of several potential scenarios for future climate policies.

Our results indicate that the implementation of the officially announced carbon policies until 2020 incurs a welfare cost of 0.3 percent and a reduction in annual consumption growth of 0.1 percentage points. In the medium term up to 2035, where we assume more stringent emission targets, welfare costs of climate policies are substantially higher but largely depend on the assumed reference growth rate. In the long run up to 2050, welfare costs of internationally coordinated emission reduction targets lie between 3 and 8 percent; the annual consumption growth rate is reduced by up to 0.4 percentage points.

We show the robustness of the results with respect to crucial assumptions. Notably, assuming a favorable technical development in the energy sector allows to cut welfare cost of carbon policy in the long run by half. Moreover, introducing energy prices increase in the reference case reduces the cost of climate policies by one third. The assumption of induced innovation has a major impact: with a lower effect than in our standard model, the cost of carbon policies raises significantly, while a high effect could even entail economic benefits of climate policies in the long run. In the same way, we confirm that the chosen discount rate has a major impact on the results. We also show that increasing urbanization will lead to slightly higher costs of carbon policies.

The paper relates to the literature in three aspects. First, it contributes to the emerging strand of literature on the integration of the *natural environment* into *endogenous growth* theory. Acemoglu et al. (2012) show that the effects and the optimal timing of environmental policy in an innovation-driven growth framework with directed technical change depend on the degrees of substitution between clean and dirty inputs. The effects of carbon policies in our multi-sector approach also rely on inter-sectoral substitution, but contrary to most directed technical change models, we assume economy-wide and not purely sector-specific knowledge spillovers.³ Bretschger and Smulders (2012) in their theoretical model derive that in a multi-sector economy increasing energy prices do not prevent an economy

³Investments are also targeted at specific sectors in our model but we argue it is more general to assume that sector specific improvements also build on improvements in other sectors through learning effects.

from having positive innovation and growth even under the conditions of poor input substitution. In a similar way, the present model implements poor input substitution in most sectors of the economy. Popp (2002) empirically estimates the effects of energy prices on energy-efficient innovations, concluding that both energy prices and existing knowledge have strongly positive effects on innovative activities. The effects of energy prices on investments will be especially modeled in our approach. With regard to climate policies, Gans (2012) derives that only policies directed at carbon pollution have an unambiguously positive impact on innovation. The results of Cullen (2013) suggest that subsidies for renewable energies are only rationalized by their environmental benefits if the social costs of pollution are sufficiently high. Finally, Allcott and Greenstone (2012) find limited scope for “win-win” opportunities with energy policy, i.e. possibilities to consume less energy without reducing welfare by removing existing inefficiencies. We derive from this literature a consensus that climate policies are costly but that cost depends on various factors, most importantly on the growth mechanisms and innovation. We show a concrete application of this general mechanism with the example of China.

In the field of *carbon policy assessment* the importance of China and its climate policy for global greenhouse gases stabilization is eminent.⁴ There are various recent contributions on China’s climate policy using computable general equilibrium. Huebler (2011) finds that the maximum welfare loss for varying energy policies between 2020 and 2050 in China amounts to four percent. By looking at disaggregated technologies, Dai et al. (2011) argue that China has to decrease coal consumption in the electricity and manufacturing sector in order to achieve the government target of 40-45 percent emission intensity reduction by 2020. Wang et al. (2009) analyze the abatement cost of different Chinese climate policy options and show that absolute emission limits similar to the Kyoto Protocol will seriously impede the Chinese development while the impact of an 80% reduction in carbon intensity by 2050 is relatively small.⁵ As reported by Financial Times,

⁴Blanford et al. (2008) conclude that effective climate policy measures must include developing and emerging countries, especially China. Wolfram et al. (2012) explain that over the next decades nearly all of the growth in energy demand, is forecast to come from the developing world, suggesting there is likely to be a large increase in the demand for energy in the coming years.

⁵Further contributions in this context are Zhang (1998), Garbaccio et al. (1999), Liang et

Beijing’s leading climate economists believe about 7.5 percent of China’s GDP in 2030 is likely to be devoted to reduce emissions.⁶ These results are related to ours but the main problem with these contributions is that they are based on either static or recursive dynamic models, which do not consider inter-temporal choices. Accordingly, these approaches cannot accommodate forward-looking savings and investment behavior as definitely required by modern endogenous growth theory. To develop a fully endogenous growth model is theoretically and numerically demanding. We show the possibility of constructing such dynamic model and its application to China in the present paper.⁷

With regard to economic *development in China* it is generally acknowledged that pace and scale of China’s economic transformation have no historical precedent, see Zhu (2012). High output growth, sustained returns on capital, and a large trade surplus are the characteristics of China’s recent development, accurately studied in Song et al. (2011) using a specially constructed growth model. They state that China’s economic transformation involve, not only rapid economic growth and sustainable capital accumulation but also shift on the economic structure and increased urbanization (see also the survey of Zheng and Kahn, 2013). Fisher-Vanden and Ho (2007) argue that a large share of total investment in China is invested unproductively by the government in pursuit of non-economic objectives. We conclude that we have to take sectoral development and urbanization into account when analyzing emission reduction policies in a comprehensive manner. In our model, urbanization will change consumption patterns affecting carbon emissions. Moreover, our approach employs two types of capital inputs for each sector, differing in terms of productivity.

The remainder of the paper is organized as follows. Section 2 develops the theoretical framework used for the numerical simulation model and derives the

al. (2007), and Vennemo et al. (2009).

⁶<http://www.ft.com/intl/cms/s/0/cd7466e8-971f-11de-83c5-00144feabdc0.html#axzz2kzFUbs5g>

⁷Other fully dynamic CGE models used to evaluate climate policies in a different context are Heggedahl and Jacobson (2011) for Norway and Bretschger et al. (2011) presenting the CITE model for Switzerland; the difference to the latter paper lies in crucial model elements like induced innovation and in the adaptation to specific issues for China like high benchmark growth, special policy targets, and special issues like the effects of urbanization. We present a largely changed version of the CITE model according to the data availability and economic structure of the country. It covers all important sectors of China’s economy.

conditions for balanced growth. Section 3 describes the data and presents a calibration of the model. Section 4 presents applications of the model and the findings from the model results. Section 5 introduces urbanization to the model and analyzes the reaction of the economy when both fast urbanization and carbon policies are taking place. Finally, section 6 concludes.

2 The model framework

2.1 Overview

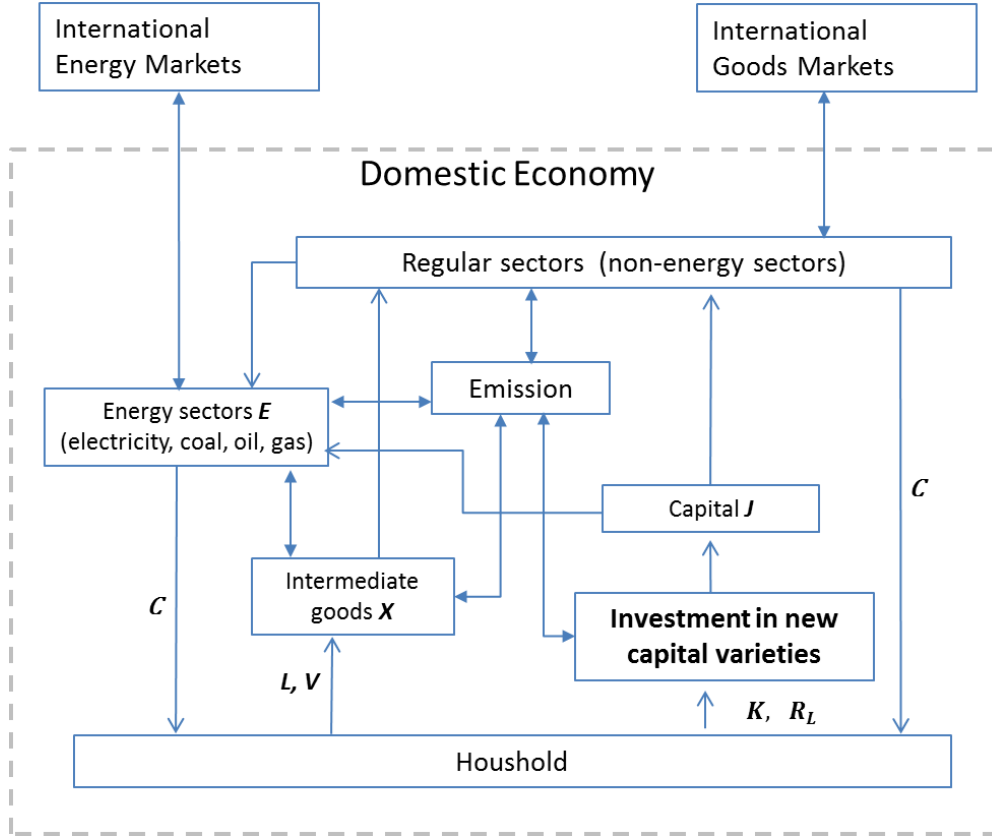
Figure 1 shows a diagrammatic sketch of the model. A representative, infinitely lived household supplies primary factors labor (L), research labor (L_R), capital (K), emission permits and other inputs (V). She allocates factor incomes between consumption and investment under perfect foresight in order to maximize inter-temporal utility. Emission permits are used in fixed proportion to energy uses based on the carbon content of the different energy sources. In order to obtain the effects of endogenous growth on long-run growth clearly, the baseline model is exempt from distortions, particularly taxes or other policies, as well as spatial considerations related to urbanization. We will distinguish between rural and urban consumers in a separate section. These two types of household are differentiated in terms of consumption preferences. In order to keep the analysis simple, we do not model regionally segmented labor markets; all sectors face the same labor supply.

2.2 Growth mechanics

Based on the expansion-in-varieties mechanism in intermediate goods of Romer (1990) we construct a fully dynamic multi-sector general equilibrium model. The main purpose is to apply a theoretically rigorous growth model in an open economy with different sectors and inputs. Because high productivity gains have been characteristic of the Chinese economy we enlarge the basic model when specifying productivity. Specifically, in each sector, output Y is produced using a sector specific intermediate composite Q and composite input from other sectors B :

$$Y = [\alpha_Q Q^{\frac{1-\gamma}{\gamma}} + (1 - \alpha_Q) B^{\frac{1-\gamma}{\gamma}}]^{\frac{\gamma}{1-\gamma}} \quad (1)$$

Figure 1: Overview of the model



where α_Q is a share parameter. Time indices are omitted whenever there is no ambiguity. The producers of Y goods maximize profits under perfect competition, i.e. they take prices of Q and B as given. The intermediate composite Q is manufactured based on Dixit and Stiglitz (1977) as well as on Ethier (1982), where q_j denotes the j th type of intermediate good and J is the total number of intermediate varieties available at a certain point of time, according to:

$$Q = \left[\int_{j=0}^J q_j^\kappa dj \right]^{\frac{1}{\kappa}} \quad (2)$$

which is the standard extension-in-varieties formulation of new growth theory with $0 < \kappa < 1$. If we assume symmetric intermediate goods, i.e. $q_j = q$, expression (2) can be simplified to:

$$Q = J^{1/\kappa-1} X \quad (3)$$

where $X = J \cdot q$ measures aggregate input in the intermediate sector. It emerges from (3) that output Q can be raised by producing larger quantity per firm q or by increasing the number of varieties (and the number of intermediate firms) J , reflecting the gains from diversification (Dixit and Stiglitz 1977). Specifically, the

term $J^{1/\kappa-1}$ measures the economies of scale on the aggregate level of the economy, because with constant X output increases in J due to increasing specialization of intermediate firms. Intermediate goods q are heterogeneous and thus incomplete substitutes among each other. Hence, each firm j providing q_j operates under monopolistic competition; the term $1/\kappa - 1 > 0$ also corresponds to the optimum markup in the intermediates' sector.

2.3 Capital accumulation

We assume each intermediate good needs one capital unit in order to be produced.⁸ Accordingly, J denotes not only the total number of varieties and firms but also the amount of capital used in the economy; $1 - \kappa$ represents the share of capital in production. With $g_J = (J_{t+1} - J_t) / J_t$ being the growth rate of capital, g_X the growth rate of intermediate production, and g_Q the growth rate of output we have from (3):

$$1 + g_Q = (1 + g_J)^{\frac{1}{\kappa}-1} (1 + g_X) \quad (4)$$

On a balanced growth path, sectoral allocation in the economy is unchanged so that the output of each intermediate good remains constant, i.e. we have $g_q = 0$. Output growth (g_Q) is then solely driven by gains from specialization, expressed by $g_Q = (1 + g_J)^{\frac{1}{\kappa}-1} - 1$. Growth is positive, provided there are positive investments ($g_J > 0$).

Capital J is accumulated through investments I according to:

$$J_{t+1} = (1 + s)[I_t + (1 - \delta_t)J_t] \quad (5)$$

where t is the time index, s the spillover of induced innovation (see next Subsection) and δ_t the depreciation rate. Investments depend on the input of research labor L_R ⁹ and on other investment specific inputs, B_{inv} , according to:

$$I = [\xi(zJ \cdot L_R)^{\frac{\omega-1}{\omega}} + (1 - \xi)B_{inv}^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}} \quad (6)$$

⁸In Romer (1990), capital is knowledge capital in the form of blueprints. We generalize the assumption to broad capital because we want to capture not only investments into non-physical but also into physical capital in the numerical simulations below. The latter constitutes an important channel for the effects of carbon policies.

⁹This variable denotes a specific type of labor, which can be derived directly from the input/output table.

where ξ and $1 - \xi$ are share parameters, ω is the elasticity of substitution, J represents the aggregate spillover of capital size to research labor productivity, and z is the spillover intensity. More specifically, we assume that the invention of new goods varieties increases the stock of public knowledge proportionally to J which is then a free input into investment activities of the next period. Hence, the knowledge spillover zJ raises research labor productivity, counteracting decreasing returns to labor in investment activities. This common mechanism of new growth theory will be present both in the benchmark scenario and the policy applications. Accordingly, carbon policies and increasing carbon prices do not affect it.

2.4 Induced Innovation

The hypothesis of induced innovation says that an increase of the price of a specific factor is a spur to innovation increasing productivity via price-induced technical progress. The seminal empirical contribution of Popp (2002) finds strong evidence for induced innovation related to energy use. Jorgenson et al. (2013, p. 481) state that “there is massive empirical evidence of price-induced energy conservation in response to higher world energy prices beginning in 1973” which leads them to conclude that a CGE model dealing with energy necessarily needs to take this into account. Because our general spillover zJ in (6) does not change the input-output relations between reference case and policy simulation we need an additional transmission channel for increasing energy prices associated to carbon policies, which we capture with our variable s , see (5). Specifically, we assume a positive impact of energy prices on investment productivity according to: 7

$$s = \max[0, \phi (p_e - p_{ref}) / p_{ref}] \quad (7)$$

where $\phi \geq 0$ measures the impact of energy price p_e on investment productivity s and p_{ref} is the (constant) energy price in the benchmark development, so that $p_e \geq p_{ref}$. We thus assume that higher energy prices, besides having negative effects by reducing intermediate goods production (see next subsection), benefit the economy through positive learning spillovers, increasing the productivity of capital investments and leading to more efficient energy use. Of course, we will carefully calibrate ϕ and test the assumption $\phi \geq 0$ in Eqn. (7) for plausibility

and robustness under different climate policy scenarios; we also discuss the case $\phi = 0$. In separate simulation we also considered the assumption of s exclusively affecting energy productivity but did not find significant changes in the results. We note that the introduction of spillovers in (5) and (6) does not create any rents which would violate the usual zero-profit conditions. However, spillovers z and s directly decrease production costs for all the firms, this also leads to accelerating the increase in the number of firms in the intermediate sector, reducing prices to eliminate rents.

2.5 Intermediate goods

Intermediate goods q_j are produced using three essential inputs: labor L , energy E , and other input V , which includes the part of capital that is not invested productively (i.e. does not accumulate like the part of capital denoted by J):¹⁰

$$q_j = J[\varphi L_j^{\frac{\epsilon-1}{\epsilon}} + \xi E_j^{\frac{\epsilon-1}{\epsilon}} + (1 - \varphi - \xi)V_j^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \quad (8)$$

with φ , ξ , and $1 - \varphi - \xi$ being the share parameters, and ϵ the substitution elasticity between the three inputs.¹¹ By multiplying the expression by J , the production of intermediates is assumed to benefit from a knowledge spillover from capital accumulation, which means that the quantity of intermediate goods increases over time with positive investments even when the quantity of the other inputs in (8) remains constant.¹²

¹⁰The main reason we distinguish between productive and non-productive capital is that a significant part of the Chinese economy is characterized by a high degree of government regulation and state-owned firms. According to previous studies in literature we thus carefully separate total capital into the two components of accumulable and constant capital, see also Section 3.

¹¹ L is different from L_R in (6) so that there is no labor reallocation between these two labor types with climate policies but our formulation of (7) captures a very similar mechanism.

¹²The assumption is necessary for the calibration of the reference case (which is a balanced growth path) but not crucial for our policy evaluations, because the effect is present both in the benchmark and with the policies.

2.6 Energy sectors

Energy (E) used for intermediate production is an aggregate of electricity E_{ele} and fossil fuels E_{fos} according to

$$E = [\delta E_{ele}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}} + (1-\delta)E_{fos}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}}]^{\frac{\sigma_{egy}}{1-\sigma_{egy}}} \quad (9)$$

where σ_{egy} is the elasticity of substitution and δ is a value share. Fossil fuels E_{fos} are further disaggregated into coal, oil, and gas, using a Cobb-Douglas function, which is omitted for the sake of brevity.

In the model, emission is a by-product of the use of energy goods for intermediate production, investment, and consumption. We assume different carbon content for various energy resources used.¹³

2.7 Sectors and trade

Below we distinguish twelve non-energy sectors (hereafter regular sectors) and four energy sectors. The output composite B in (1) reflects inter-sectoral linkages through the input-output structure of the economy. China trades with the rest of the world (aggregated into one region) on all markets for final goods Y and uses Armington demand functions to model trade, where goods of each sector are differentiated by the region where they are produced. Markets for final goods are perfectly competitive and provide goods for domestic use (D) or exports (P):

$$Y = [\alpha_d D^{1+tr} + (1-\alpha_d)P^{1+tr}]^{\frac{tr}{1+tr}} \quad (10)$$

where α_d is the share of domestic use in total output Y and tr is the elasticity of substitution between D and P . There is imperfect substitution between domestically produced goods Y and imported goods M :

$$A = [\nu M^{\frac{\eta-1}{\eta}} + (1-\nu)Y^{\frac{\eta-1}{\eta}}]^{\frac{\eta}{\eta-1}} \quad (11)$$

where ν and $1-\nu$ are the value shares and η is the elasticity of substitution. We assume that foreign prices are given and asset trade is disregarded in the model, so

¹³Based on the data from IPCC and China, the carbon content of gas is normalized to unity, the carbon content of coal is 1.68, oil is 1.26, and electricity 1.51 relative to gas.

that goods trade is balanced in each period.¹⁴ In each sector, the market clearing condition requires that supply equals demand.

2.8 Welfare and Consumption

Total welfare is derived from individual utilities according to:

$$W = \left[\sum_0^t \left(\frac{1}{1+\rho} \right)^t C^{1-\theta} \right]^{\frac{1}{1-\theta}} \quad (12)$$

where ρ is the utility discount rate and θ is the elasticity of inter-temporal substitution. C represents an aggregate of different goods, consisting of consumption of a regular sector output composite (C_y) and an energy aggregate (C_e) with an elasticity of substitution (σ_C):

$$C = \left[\zeta C_y^{\frac{\sigma_C-1}{\sigma_C}} + (1-\zeta) C_e^{\frac{\sigma_C-1}{\sigma_C}} \right]^{\frac{\sigma_C}{\sigma_C-1}}. \quad (13)$$

The regular sector output composite (C_y) is given by a Cobb-Douglas function, according to:

$$C_y = \prod_{ne} C_{ne}^{\beta_{ne}} \quad (14)$$

where subscript ne is a set containing twelve non-energy goods, β_{ne} shows the consumption shares of each goods respectively. We further disaggregate the energy composite into fossil aggregate and electricity consumption with an elasticity of substitution σ_{ce} :

$$C_e = \left[\iota C_{ele}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} + (1-\iota) C_{fos}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} \right]^{\frac{\sigma_{ce}}{\sigma_{ce}-1}} \quad (15)$$

where ι is the value share of electricity consumption in total energy aggregate and the fossil aggregate (C_{fos}) is given by

$$C_{fos} = C_{coal}^{\alpha_{coal}} C_{oil}^{\alpha_{oil}} C_{gas}^{\alpha_{gas}} \quad (16)$$

¹⁴It is true that China experiences trade surplus due to its export-oriented development strategy. If we embody this fact into our benchmark, the effect of trade surplus will exist both in benchmark and policy scenarios. When we compare the effects of carbon policy on growth to the benchmark case, such effects are marginal because most of them are canceled out. Hence, the assumption of balanced trade is not likely to affect our estimation results significantly.

where α_{coal} , α_{oil} , α_{gas} are the respective energy source consumption share in fossil aggregate with $\alpha_{coal} + \alpha_{oil} + \alpha_{gas} = 1$.¹⁵

3 Data and calibration

3.1 Input output table

The model builds on data from the Chinese input-output table (IOT) of 2010. There are good reasons to use this table: 1) it contains sufficient information on intermediate and factor inputs of the different sectors; 2) it provides information on the production structure of the four major energy sources; 3) it describes demand for non-energy and energy goods; 4) it captures necessary information on investment and R&D; 5) it distinguishes between rural and urban consumers.

We introduce twelve non-energy (regular) sectors which are agriculture (*agr*), mining (*min*), chemical industry (*chm*), machinery industry (*mch*), other industries (*oin*), construction (*con*), transport (*trn*), banking and financial services (*bnk*), private services (*pse*), government and public services (*gse*), real estate (*rea*), water supply industry (*wat*) and four energy sectors, i.e. electricity (*ele*), coal (*coa*), oil (*oil*), and gas (*gas*).

3.2 Capital share

An important issue for a dynamic model is the capital share of the economy. Fleisher et al. (2010) find that it is between 0.18 and 0.52, depending on the model specifications. Following Bai et al. (2006), Song et al. (2011) use a value of 0.5 for their numerical studies. These high capital shares are a consequence of the high savings rate but also due to the fact that all these studies do not consider energy as a separate input of production. However, in the input/output data we use it turns out that the energy share of GDP is much higher than in other (developed) economies, at about 20 percent. Furthermore, Bai et al. (2006) find evidence of misallocation of investment in China and an overestimation of capital share in statistics. To reflect the part of less productive capital, we distinguish

¹⁵The remaining equations for model closure are the standard equations on zero-profit conditions, and thus do not yield additional insights; they are available from the authors upon request.

two types of capital: non-accumulative capital and accumulative capital. Non-accumulative capital enters the production function as an additional input besides labor and energy. Only accumulative capital contributes to the creation of new knowledge. For the accumulative capital we relate to Kuemmel et al. (2002), who estimate an average level of 0.25 for comparable growth miracles such as Japan and Lu and Zhou (2009), who estimate the cost share of capital in the periods 1978-2005 for China to fluctuate between 0.10 and 0.30. Accordingly, we assume the share of accumulative capital to be 0.25 in this study.¹⁶ Because we also include (sector-specific) non-accumulative capital the average capital share of the benchmark economy amounts to around 40 percent on average.

3.3 Other assumptions

The prices of all goods are assumed to be constant in the benchmark, which is the usual assumption for CGE models.¹⁷ We will test the impact of increasing energy prices due to increasing scarcities in a separate section below. To determine induced investment reflected in (7) we refer to the estimation of Popp (2002) who reports a long run elasticity between 0.354 and 0.421 for (energy-related) technology patents with respect to energy prices. We use a value of ϕ of 0.2 in all the sectors in the first part of the study and test for sensitivity in a separate section below.

Table 1 provides the parameter values for the different elasticities we use for numerical simulation. The values are taken from existing studies, specifically van der Werf (2007), Okagawa and Ban (2008), Hasanov (2007), and Donnelly et al. (2004). As customary in applied general equilibrium analysis we use economic value flows of the dataset to calibrate the value share and level parameters for the base year of the model. The model is calibrated to a steady-state baseline extrapolated from the base-year IOT with assumptions on growth rate of output,

¹⁶In the benchmark, the 25% applies for all the sectors, which is a necessary assumption for balanced growth. We run sensitivity check with lower and higher value of capital share, and find higher share of capital will lead to a relatively higher cost for the same emission reduction because higher capital share means lower share of energy input in production, which potentially increases the productivity of energy, and hence carbon reduction policy will raise the energy prices further relative to lower capital share case. In contrary, lower capital share declines the cost for carbon mitigation. However, such changes in cost are small.

¹⁷Specifically in the dynamic model setup, the price path over time in terms of present value in the model is calibrated to decline with a rate of $1/(1+r)$, where r is the interest rate.

interest rate, depreciation.

Table 1: Parameter values for regular sectors and consumption

Parameter	Description	Value
γ	Elasticity of substitution between Q and inputs from other sectors B	0.392 (agr) 0.848 (coa, oil, gas, ele, chm) 0.518 (mch) 0.500 (min) 1.264 (con) 0.352 (trn) 0.568 (oin) 0.492 (rest)
ε	Elasticity of substitution between the three inputs (Energy E , labor L and other inputs V)	0.7 (agr, coa, oil, gas, ele, chm) 0.8 (mch) 0.52 (con) 0.82 (oin) 0.5 (min) 0.4 (rest)
ω	Elasticity of substitution between investments in R&D (B_{inv}) and research labor L_R	0.3
σ_C	Elasticity of substitution between energy (F) and non-energy goods (D) in consumption	0.5
σ_{egy}	Elasticity of substitution between electricity and fossil fuels in intermediate production	0.8
σ_{ce}	Elasticity of substitution between electricity and fossil fuels in consumption	1.5
θ	Inter-temporal elasticity of substitution in the welfare function	0.6
η	Trade (“Armington”) elasticities	3.2 (agr) 4.6 (mch) 3.8 (oin) 2.9 (rest)
tr	Elasticity of transformation	1
v	Elasticity of substitution between sectoral outputs for the input B	0
ϕ	Impact of energy price on innovation	0.2

3.4 Time frames

We consider three different time frames for our analysis: short term (2010-2020), mid term (2010-2035), and long term (2010-2050); they differ in terms of reference growth rates and policy targets. We construct three different baseline scenarios that are designed to reflect different time frames with corresponding differences in assumed reference growth rates. The reference growth rate in the short run is assumed to be 7 percent per year, based on the 12th Five-Year-Plan report of the Chinese government, which is our reference to study the carbon policies up to

2020. Two different reference growth rates (4 percent and 7 percent) are used for the analysis of medium run scenarios with a focus on economic effects of carbon policies advocated by the International Energy Agency (IEA). In the long run, the economy is assumed to grow at an average annual rate of 4 percent in the benchmark; carbon policy targets are based on international burden sharing rules which are currently discussed for a global climate agreement. The real interest rate is assumed to be 4% following World Bank data. According to the calibration procedure, the discount rate is implicitly determined by the real interest rate, the reference growth rate of output, and the inter-temporal elasticity of substitution.

3.5 Benchmark

All policies scenarios are compared to a benchmark. In our multi-sector economy, the benchmark is assumed to be a balanced growth path meaning that all sectors grow at the same steady-state rate; i.e. there is no structural change. The population is assumed to be constant over time (a realistic assumption for China); hence, aggregate work and research labor remain unchanged. The varieties in production expand over time, entailing spillover effects and increasing productivity of intermediate goods' production. According to Equation 4, an increasing variety of goods (increasing output) can be produced with a given amount of input, which is the source of endogenous growth in our model. In the benchmark, there is no specific investment induced by changing energy prices because these are constant (i.e. $s = 0$). As the carbon contents of energy sources are fixed, emissions grow at the rate of energy and general output in the benchmark.

4 Implementing carbon policies

4.1 Policy scenarios

China has enacted several national and provincial energy saving regulations and codes to achieve carbon emission reductions. Prominently, the 12th of China's five-year plans for the period 2011 to 2015 aims at an emission intensity reduction of 17% in 2015 against the 2010 value. A long-term target of 40-45% emission intensity reduction in 2020 against the 2005 level has also been specified by the

government.¹⁸ These policies will be labeled *CHN40* and *CHN45* below. The proposal is less stringent than other countries' announcements such as the U.S. target of a 17 percent reduction of greenhouse gases¹⁹ by 2020 against 2005 because for a fast-growing economy, absolute emissions would still keep growing significantly.

China has recently evaluated the policy of emission cap from 2016 on. But according to the International Energy Agency (IEA 2010), it will likely continue to increase emissions until 2020, emitting 20% more compared to 2010. In the IEA 450 ppm scenario, which we label *IEA450*, (absolute) emissions in China will start to decline only after 2020. Under *IEA450*, total emissions in 2035 are about 71 percent of the 2010 level. The *IEA450* scenario stops in 2035, but worldwide climate policies are now formulated until 2050. Hence, two scenarios with long term goals will also be considered: *CER524* and *CER361*. These two scenarios are derived from the contribution of Bretschger (2013). He proposes a general synthetic rule for burden sharing in international climate agreement based on general equity principles, finding that an average budget per capita per year in the period 2010-2050 for China is 5.24 tons in the most favorable case (labelled *CER524*), and 3.61 tons in the most unfavorable case (*CER361*).²⁰ Considering that Chinese per capita emission in 2010 were 5.4 tons (IEA 2010), total reduction in emissions between 2010-2050 is 3 percent in *CER524* and 33 percent in *CER361*, respectively. In addition, we study - as a reference policy scenario - a path where the emission level is kept constant at the level of 2010 until 2050 (*ZERO*).

Overall, we evaluate six climate policy scenarios: two government target scenario in the short run (*CHN40* and *CHN45*); one scenario in the mid-term,

¹⁸As in 2010, 21% emission intensity reduction has been achieved compared to the level of 2005. China needs a reduction of emission intensity by 24% and 30% in 2020 from 2010 level to reach the 40% and 45% target between 2005 and 2020 respectively.

¹⁹The target of the U.S. is based on the UNFCCC report. http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php.

²⁰We note that these two scenarios show only what China should do disregarding the policies implemented in other countries. One way of introducing policy effects of foreign countries in our one region model framework is to vary the value of trade elasticity. If foreign countries implement less stringent carbon policy, the prices of fossil energies in China are higher than abroad. This will increase the incentives to import goods rather than producing in domestic firms. Hence, trade elasticity rise, as there is an increased preference for foreign goods. On contrary, we can decrease the value for trade elasticities to formulate the case where foreign countries implement more stringent carbon policies than China. The appendix shows such sensitivity analysis.

namely *IEA450*; two scenarios for the long run, *CER524* and *CER361*; and, in addition, one scenario for all three time frames with constant emission level over time (*ZERO*). Technically, the emission targets are achieved by imposing carbon taxes for energy use and consumption according to the carbon content of various energy sources. Tax revenues are redistributed to consumers as a lump-sum transfer.

Figure 2 depicts the CO₂ emission profiles across scenarios in China. As the economy grows at the rate of 7 percent per year, China will emit 14,278 Mt CO₂ in 2020, which doubles the 2010 level (7258.5 Mt according to IEA(2010) estimation). For the two government target scenarios, the CO₂ emission in 2020 is 10,852 Mt in *CHN40*, and 9,995 Mt in *CHN45*, resulting in a decline in emission by 24 percent and 30 percent respectively compared to the reference scenario. However, this is up to 50 percent increase relative to the emission level in 2010. The absolute emission keeps growing at a relatively lower rate compared to the reference scenario. These two government scenarios allow more emission than *IEA450* which estimates the emission in 2020 is 9,030 Mt. *CER524* and *CER361* have the same emission limitation for the year 2020. Before 2020, all the five scenarios have an increase in CO₂ emission, showing limited efforts for emission mitigation. The distinction happens after 2020. *IEA450* requires emissions to go down to 5,164 Mt in 2035, where in *CER524* 6,097 Mt in 2035 is allowed, 18 percent higher than the level of IEA. The most stringent target is to keep the carbon emission at the level of 3,121 Mt after 2035 in *CER361*, up to 39 percent lower than the IEA level. Table 2 summarizes all scenarios implemented in this section.

4.2 Results of cost estimations

4.2.1 Short run (2010-2020)

Figure 3 shows the growth path of aggregate consumption over time across scenarios. Given the high growth rate consumption increases by a factor of two between 2010 and 2020. For the two government scenarios *CHN40* and *CHN45* we obtain a growth rate of around 6.91 percent against 7 percent in the benchmark. The discounted welfare loss of the two climate policies is 0.32 percent and 0.34 percent. In scenario *ZERO*, the welfare loss associated with keeping the emission

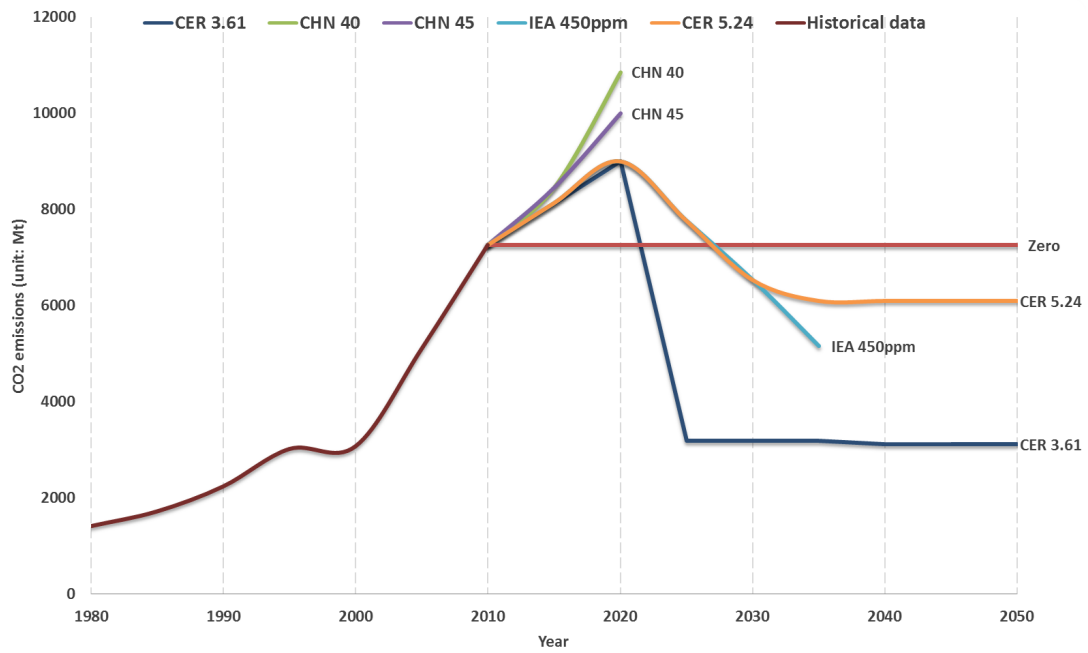


Figure 2: CO2 emission trajectories across scenarios

level constant is 0.84%.

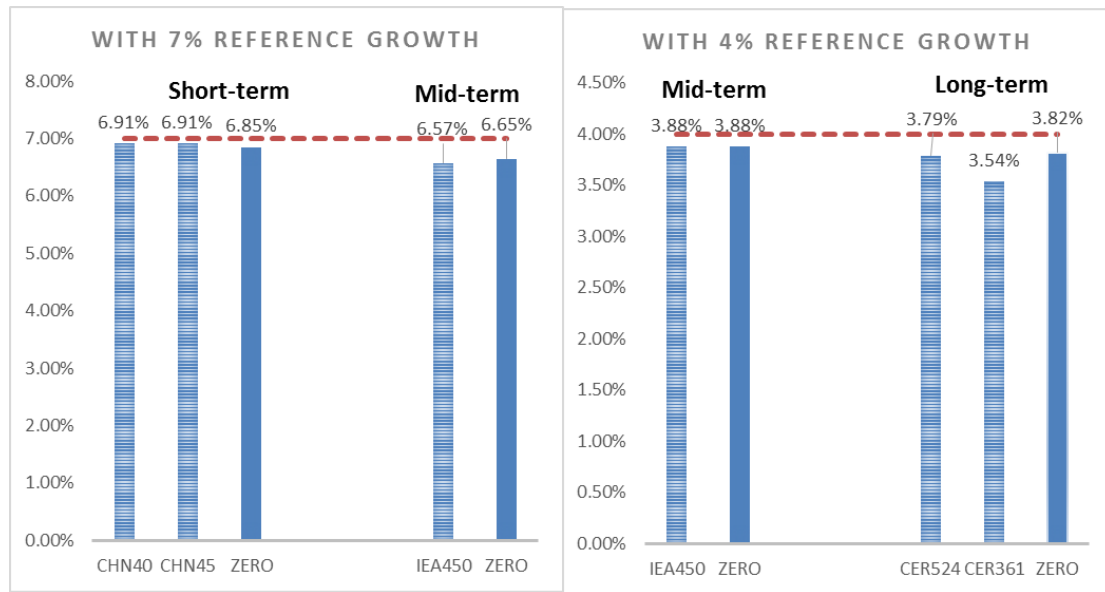


Figure 3: Annual average growth rates of aggregate consumption under different time horizons

4.2.2 Medium run (2010-2035)

For the medium run we consider two reference growth rates: 7 and 4 percent. Assuming the 7 percent growth from the short run the welfare loss is 7.23 percent in the *IEA450* scenario with an average growth rate of consumption at 6.57

Table 2: Description of scenarios in section 3.2.2

Scenario	Time periods	Reference Growth rate	Carbon policy Definition
Short-term			
CHN40	2010-2020	7%	40% carbon intensity reduction
CHN45	2010-2020	7%	45% carbon intensity reduction
ZERO	2010-2020	7%	Constant emission level (5.4t per capita per year)
Mid-term			
IEA450	2010-2035	7%	Emission profile defined in 450ppm scenario by IEA
ZERO	2010-2035	7%	Constant emission level (5.4t per capita per year)
IEA450	2010-2035	4%	Emission profile defined in 450ppm scenario by IEA
ZERO	2010-2035	4%	Constant emission level (5.4t per capita per year)
Long-term			
CER524	2010-2050	4%	Carbon budget of 5.24t per capita per year
CER361	2010-2050	4%	Carbon budget of 3.61t per capita per year
ZERO	2010-2050	4%	Constant emission level (5.4t per capita per year)

percent. As a comparison, to keep CO2 emissions constant (in *ZERO*) the loss in welfare amounts to 5.35 percent. Comparing these results to the short run we find two interesting issues. First, cost of carbon mitigation increases with time, even with the normal assumption of a positive discount rate. The reason is that emission cuts have higher costs with a higher income level. Specifically, in the *ZERO* scenario it can be seen that the cost of the policy for the first 10 years is 0.84 percent, while the cost for the next 15 years is 4.51 percent. Second, and related to that, it is not beneficial but costly to delay emissions to later periods. The reason is that an earlier redirection of inputs towards investment and growth is beneficial in our growth model. Notably, in *IEA450*, emission reduction mostly happens in the last 10 years (2025-2035) which leads to a substantial increase in welfare cost of carbon policy.

Suggesting that 7 percent annual growth up to 2035 is a too ambitious target we now reduce the reference growth rate of the economy to 4 percent in the baseline. It can be seen from Figure 3 that a lower reference growth rate makes it easier for the economy to reach the emission target, as could be expected. Consumption growth in the two policy scenarios is now 3.88 percent. Remarkably, the welfare loss in both scenarios is less than one fifth of the value with 7 percent reference growth (1.34 and 0.94 percent). Hence, even in our endogenous growth model, the cost of carbon emission mitigation increases drastically with the reference growth rate of the economy. There are two reasons for this huge difference. First, a lower GDP growth rate means lower CO2 emissions so that

the differences between baseline and emission mitigation targets become smaller. Less resource and effort are required for the emission reduction with lower GDP growth. Second, in our fully fledged intertemporal approach, a lower growth rate of the economy implies a higher discount rate²¹ which reduces the present value of future cost. As the welfare loss is computed as the accumulative discounted present value over time, the estimated cost is smaller compared to the case of high growth.

Table 3: Welfare loss across scenarios with different time frames

With 7% reference growth					
Time frame	short-run (2010-2020)			medium-run (2010-2035)	
Scenarios	CHN40	CHN45	ZERO	IEA450	ZERO
Welfare loss	-0.34%	-0.32%	-0.84%	-7.23%	-5.35%
With 4% reference growth					
Time frame	long-run (2010-2050)			medium-run (2010-2035)	
Scenarios	CER524	CER361	ZERO	IEA450	ZERO
Welfare loss	-3.10%	-8.33%	-2.57%	-1.34%	-0.94%

4.2.3 Long run (2010-2050)

For the long run we assume the reference growth rate of the Chinese economy being 4 percent per year. Enforcing a constant emission level over time (scenario *ZERO*) the growth rate of consumption becomes 3.82 percent, which is somewhat lower than the rate in the medium run. Because development is less dynamic and the time horizon is longer, we obtain a welfare loss of 2.57 percent for this policy. The first case of burden sharing from the global perspective (*CER524*) suggests similar results, the welfare loss amounts to 3.10 percent. *CER361* showcases the most stringent climate policy scenario. The growth rate of consumption drops to 3.54 percent and welfare loss rises up to 8.33 percent, which is the highest value we obtain in the present setup.

Given the various modeling and parameter choices we made to obtain these results we have to do extensive sensitivity analysis, to which we turn next.

²¹Following the standard calibration procedure and given the real interest rate and intertemporal elasticity of substitution, the discount rate is then defined implicitly by the growth rate of output. See Rutherford (2004) and Ramer (2011) for more details.

4.3 Sensitivity analysis

There are several model issues which might be important for our results and therefore deserve closer attention. First, our model includes general learning effects but does not assume a specific technology development for the future. However, from the perspective of engineering, the development of new technologies e.g. for electricity generation from renewable energy sources as well as novel technologies for carbon capture and storage (CCS) are relevant scenarios. Second, we have assumed constant energy prices in the reference case. But as soon as increasing scarcities entail increasing energy prices (independent of any policies), the evaluation of these policies looks different. Third, varying the size of the learning effects induced by increasing energy prices affects the results. Fourth, we have to reconsider the issue of discounting in our endogenous growth model. Finally, the assumed elasticities of substitution have to be varied to see their impact on the final results.

4.3.1 Green technologies

In addition to general efficiency improvements there are two specific technical approaches to reduce greenhouse gas emissions. One is to develop and use renewable energies which are CO₂ free. To promote renewable energies China has enacted its Renewable Energy Law. A specific goal for renewables is also set out in China's 12th Five Year Plan, which specifies values of 11.4 percent for total primary energy from non-fossil sources by 2015 and 15 percent by 2020; the current level is 8 percent. 20 percent of current electricity generation is attributed to renewable resources, 18 percent stems from hydropower. The other technology option is to reduce future CO₂ emissions by adopting CCS. China runs one of the largest numbers of CCS pilot projects in the world. Operations of the projects include state-owned power generation, coal and oil companies.

To specify this technology evolution, we now assume a declining trend of carbon content of energy input. We consider two alternative scenarios: one showing the carbon content of electricity only declining to half of 2010's level in 2050 (labeled *TC for ele*), the other reflecting a declining carbon content of all energy source to half of their 2010's levels respectively (*TC for all*).

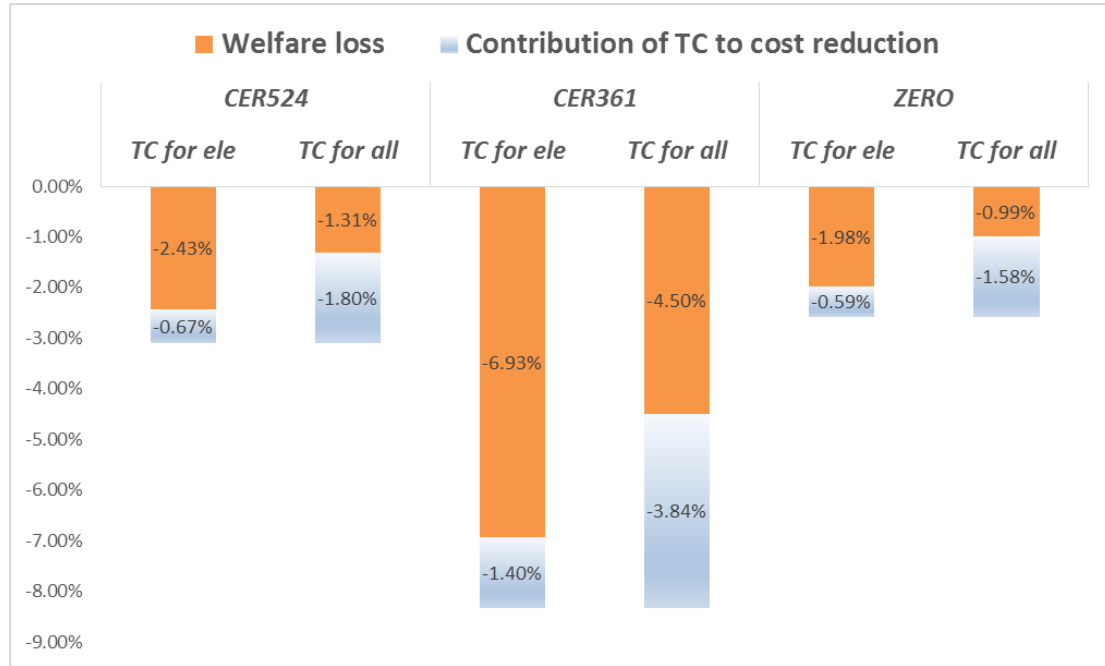


Figure 4: Aggregate effects comparison with green technology development in the long run

Results in Figure 4 confirm that cost for carbon mitigation can be reduced if renewables are introduced as a substitute for polluting energies. As compared to our previous results, welfare losses decrease in all three carbon policies. The reduction is much larger when technologies such as CCS can be used to decline the carbon content of fossil energies. In the most stringent scenario *CER361*, welfare loss of carbon policy drops from 8.33 percent to 4.5 percent, accounting for approximately half of the total welfare loss. Accordingly, aggregate consumption growth is higher than in the case without a specific technology development.

We note that the improvement of efficiency in CCS and the expansion of renewable energy in electricity generation involve additional investments which are excluded from the calculation. Hence, our estimation of the contribution of exogenous technical change to cost reduction may be overestimated.

4.3.2 Energy price effects

Based on the theory of nonrenewable resources as developed in Hotelling (1931), the optimum extraction path for non-renewable resources is one along which the resource rent increases at the rate of interest. To reflect the development path of energy prices according to the Hotelling framework for nonrenewable resources, we run separate scenarios (i.e. a series of *PR* scenarios with different time frames

and growth rates of output) assuming that energy prices increase with the interest rate, i.e. by four percent per year in our numerical simulation.

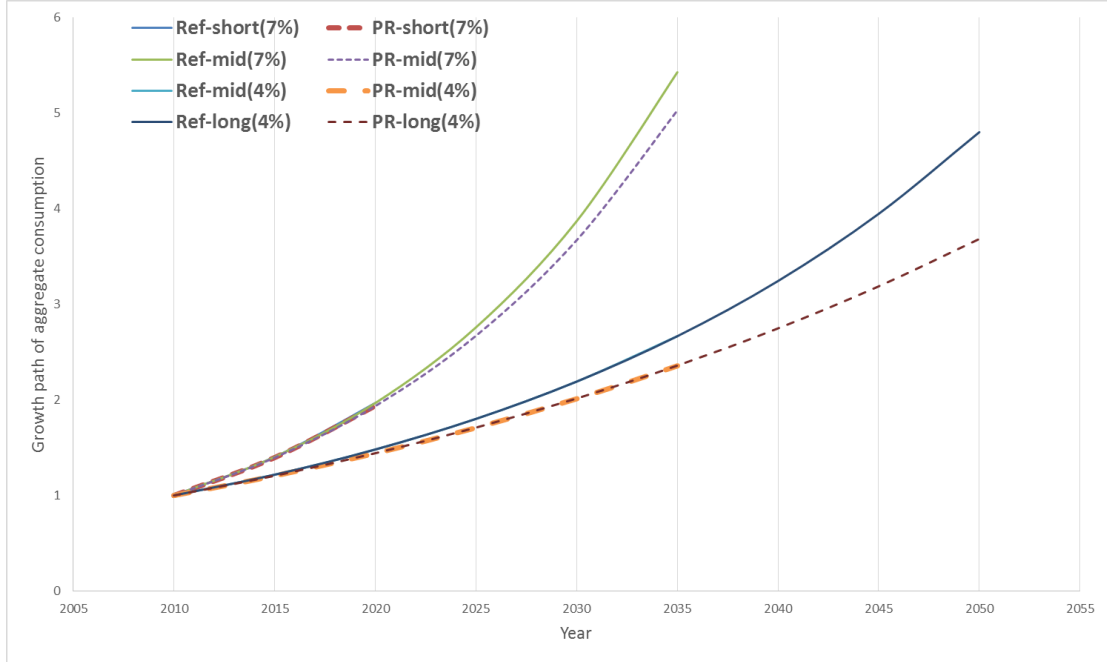


Figure 5: Consumption over time with increasing energy price

As illustrated in Figure 5, higher energy price discourages energy consumption and increases prices of consumer goods, especially energy intensive goods. Under such conditions, consumption growth is lower than in the reference case, where energy prices are assumed to be flat. The average short run growth rate of consumption is 6.83 percent (level of reference is 7 percent). Consumption is not very sensitive to the prices in the short run but significant in the longer run, especially in the scenarios with relatively low growth rates of output.²²

To determine induced investment reflected in (7) we refer to the estimation of Popp (2002), who reports a long run elasticity between 0.354 and 0.421 for (energy-related) technology patents with respect to energy prices. As shown in Table 4, the positive effect of induced innovation alleviates the negative impact of energy price increase. The positive effect increases in the value of ϕ . So far we have assumed ϕ to be 0.2, the consequences of reducing it to 0 (no learning

²²The welfare loss of the path with increasing energy prices is 2.2 percent relative to the reference case with constant energy prices in the short run. The loss of welfare increases to 5.5 percent with a growth rate of 6.68 percent per year in the mid-term time until 2035. If the output grows at 4 percent per year in the reference, the loss of welfare increases to 8.5 percent with a growth rate of 3.51 percent per year in aggregate consumption. The long-run effect is much stronger, aggregate consumption growth drops from 4 percent to 3.33 percent, accounting for 12.44 percent welfare loss.

spillovers from increases energy prices) and doubling to 0.4 are also given in Table 4.

Table 4: Aggregate effects of increasing energy prices with induced innovation

Value of ϕ	Welfare change			consumption growth
	price effect	induced invest effect	aggregate effect	aggregate
$\phi = 0$	-12.44%	0	-12.44%	3.33%
$\phi = 0.2$	-12.44%	+10.31%	-2.13%	3.85%
$\phi = 0.4$	-12.44%	+19.94%	+7.5%	4.17%

Induced innovation (the magnitude of ϕ) has a significant impact on the effects of carbon policies. It can convert a relatively high welfare loss in the case of no induced innovation ($\phi = 0$) into a welfare gain, constituting a “win-win” situation which one might call successful “green growth”. Based on empirical evidence and because we do not want to assume a value which is overly optimistic we stick with $\phi = 0.2$ in the main analysis.

In absence of induced innovation, the welfare loss of the economy is about 12.44% under the Hotelling pricing assumption. With regard to energy price development, all three long-run carbon reduction scenarios lead to an increase of energy price of more than 4 percent (our Hotelling case), meaning that carbon policies further increase the price of energy. Hence, if we think that Hotelling forces will come into play in the future, the estimated welfare losses above implicitly contain the effects due to the Hotelling price change. It is then illuminating to subtract the effects of the Hotelling energy price path from our estimations.²³ Figure 6 shows that, after separating the Hotelling energy price effect, the maximum welfare loss from *CER361* declines to 6.20 percent. Put differently, the average carbon budget per capita per year in the benchmark has to be around 13.4 tons to sustain annual growth of 4 percent until 2050. The Hotelling energy price path reduces the carbon budget to 7 tons, which accounts for up to 80 percent emission reductions in the carbon policies scenarios. We conclude that in a world with increasing energy prices, emissions will be implicitly reduced through the price effects (both negative price increasing effect and positive price-induced innovation effect), and the required policy efforts to reach long-run emission targets become substantially lower, which also applies to the welfare losses.

²³To decompose the effects of induced innovation from aggregate effect in Table 4, we assume the (Hotelling) price effect in all three scenarios is the same, the residual between price effect and aggregate effect gives the effect attributed to induced innovation.

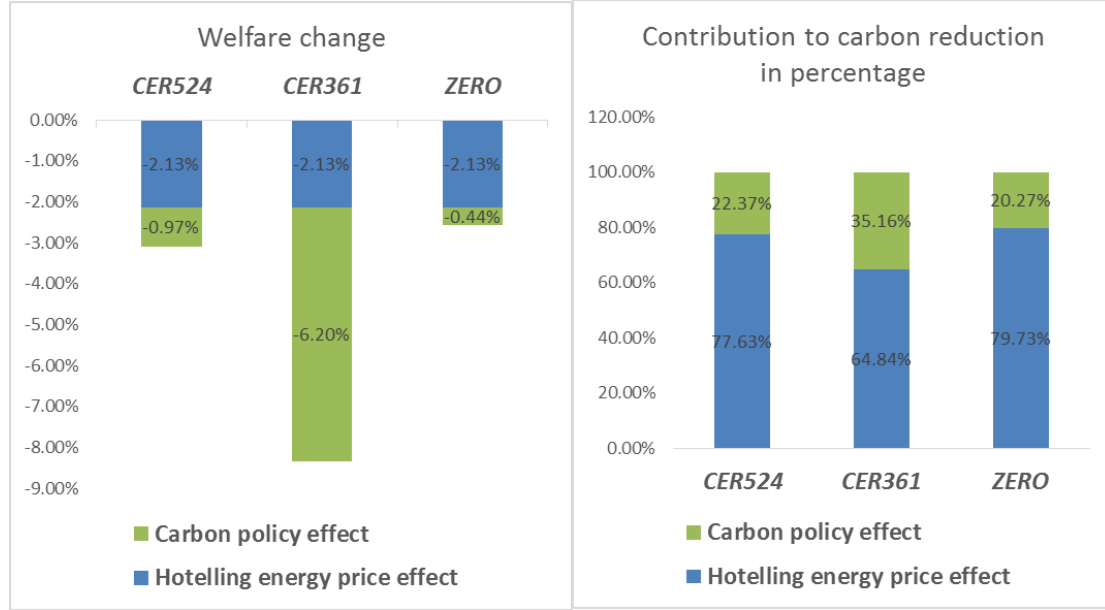


Figure 6: Decomposition of Hotelling price effect and carbon policy effect

4.3.3 Discounting

The choice of the discount rate will affect the estimation in the long run. The model calibration for the above analysis implicitly assumes a discount rate of 1.6 percent in the model. The social planner might prefer a different discount rate to market participants and use a value of 4 percent, which is frequently used in climate policy. Using the reported consumption path from the model and together with the discount rate of 4 percent, the welfare level associated with the new discount rate can be calculated using equation 12 separately. We call this a “static approach” to welfare estimation. The higher discount rate leads to a sharp reduction of welfare loss. The cost of carbon mitigation policy in scenarios *CER524*, *CER361*, *ZERO* now become 0.81 percent, 3.1 percent, and 0.79 percent, respectively. The reason is that the planner values future consumption losses due to climate policy less than the households.

Instead, a “dynamic approach” analysis is conducted if we impose the higher discount rate to the individuals. The difference between the static and dynamic approach is that interest rate will be adjusted accordingly in a dynamic context. The intertemporal optimization of consumption (Keynes-Ramsey rule) suggests that the market interest rate has to rise as well, in our case from 4 percent to 6.4 percent. The reason is that the benchmark path is determined by a given growth rate. It is then still true that higher discounting reduces the cost of climate

policies. But the welfare loss does not decline by a large amount compared to the original estimation since a higher interest rate makes it more expensive to invest in capital and to substitute for fading energy input. This is confirmed by the results from Table 5 which shows lower growth rates of consumption in the case of 4 percent discounting compared to the case of 1.6 percent discounting.

Table 5: Aggregate effects comparison with different inter-temporal discounting rates in the long run

Scenarios	Welfare change			Aggregate consumption growth		
	1.6% (benchmark)	4% (dynamic)	4% (static)	1.6% (benchmark)	4% (dynamic)	4% (static)
<i>CER524</i>	-3.10%	-2.83%	-0.81%	3.79%	3.77%	3.77%
<i>CER361</i>	-8.33%	-7.02%	-3.10%	3.54%	3.53%	3.53%
<i>ZERO</i>	-2.57%	-2.46%	-0.79%	3.82%	3.82%	3.82%

4.3.4 Substitution elasticities

Finally, additional sensitivity analysis on the values of the substitution elasticities are conducted to check the robustness of our results. The Appendix summarizes these results on parameter sensitivity, indicating the high reliability and robustness of our results on the cost of carbon policy.

4.4 Results of structural change

Because the model contains many sectors with important intersectoral linkages, the structural aspects of development are worth considering. In the reference case, all the sectors grow at the rate of aggregate output. But carbon policies have an impact on sectoral growth and thus change the sectoral structure of the economy. In general, energy intensive sectors tend to shrink while knowledge intensive sectors are able to grow faster.

As shown in Figure 7, climate policies affect sectoral development. In the general model, technological change and efficiency improvement stem from two substitution effects: (i) substitution between energy input and other inputs (for instance, work labor), because the price of other inputs is relatively cheaper than energy since emission cap implicitly increases the price of energy; (ii) investment in research and the spillover effects from research labor. Innovative sectors which are capital intensive in the baseline can adjust easier and alleviate the shocks from

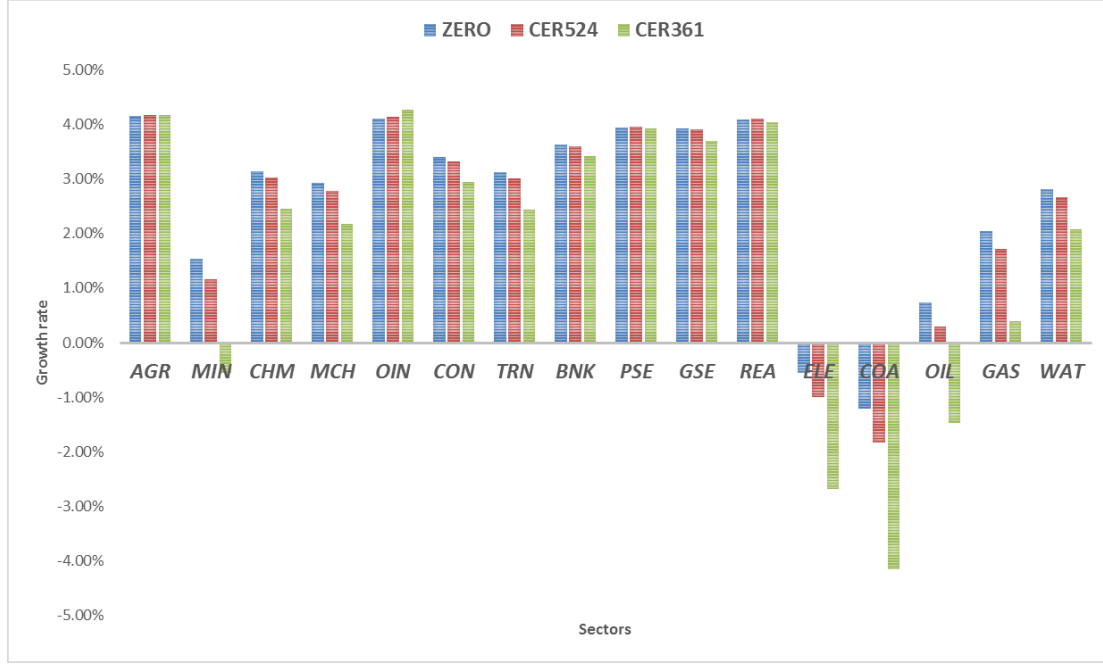


Figure 7: Effects of carbon policies on sectoral growth in the long run

carbon tax. These two forces come from the setup of the model (see Equations 6 and 8) and can be observed from the change in the growth rates of regular sectors.

Energy intensive sectors such as Mining industry (*min*), machinery (*mch*), construction (*con*), transportation (*trn*) shrink compared to sectors such as agriculture (*agr*), which is labor intensive and private service sector (*pse*), which is capital intensive. Particularly, the *min* sector, as a source of primary energies, will experience a decline in production since less fossil energies are demanded in the future. It is worth noting that water supply industry (*wat*) declines substantially as well. This confirms the information that converting primary energy into end use energy requires a great deal of water. Hence, demand for water declines as the energy sectors shrink.

As targeted by the policy, the energy sectors suffers from the adopted policies. Within the energy sectors, two substitution effects are effective. The first is substitution between the three fossil energies. Energy sources with higher carbon content can be replaced by sources with lower carbon content since higher carbon content implies that higher tax is imposed for that energy source. It is clear from the figure that coal suffers the most. It shrinks with a rate of between -1.22 percent in *ZERO* and -4.15 percent in *CER361*, followed by oil, which still grows at a rate of 0.74 percent in *ZERO* but shrinks with a rate of -1.47 percent in

CER361. The change of the growth rate in gas is insignificant between *ZERO* and *CER524*. To achieve the most stringent target in *CER361*, the production of gas has to keep almost at current level. The dependency on natural gas will have to increase since it is relatively cleaner energy source compared to others. The second effect is substitution between electricity and fossil energies. Acceleration of electrification makes it relatively easier to substitute. Specifically in China, substantial investments in power plants and grids construction enlarged the penetration rate of electricity distribution and electric equipment. However, most of the power plants in China are still coal-fired, which means electricity is carbon intensive relative to, for example, gas. This can lead to an “inverse” substitution between electricity and fossil bundles. We can see from the figure that the growth rate of electricity is much lower than two of the three fossil energies in all scenarios. The decline in electricity growth is large. It drops to -0.55 percent in *ZERO* and -2.68 percent in *CER361*, which provides evidence that the second inverse substitution effect is dominant.

Figure 8 offers an overview of the change in energy mix over time across scenarios. *ZERO* shows a clearly rising share of gas and oil, and a substantially decline in the share of coal and electricity. This result illustrates an induced transition towards cleaner energy sources when climate policy is binding. The sub-figure in the bottom right illustrates the correlation between energy consumption and CO₂ emission. With the emission reduction, total energy consumption also declines.

5 Urbanization and sectoral change

As predicted by the United Nations (2013), by 2050 total population in China will remain almost at today’s level²⁴, even though it first increases to peak around 2025 and declines afterwards. The most dominant demographic effect is urbanization. The rate of urbanization is seen as a sign of success of economic achievement. China’s population urbanization rate in 2010 reached about 50 percent from 10.6 percent in 1949, showing a significant urbanization development pro-

²⁴The UN report predicts the total population of China is 1.449 billion in 2025, and 1.385 billion in 2050, and the population in 2013 is 1.386 billion.

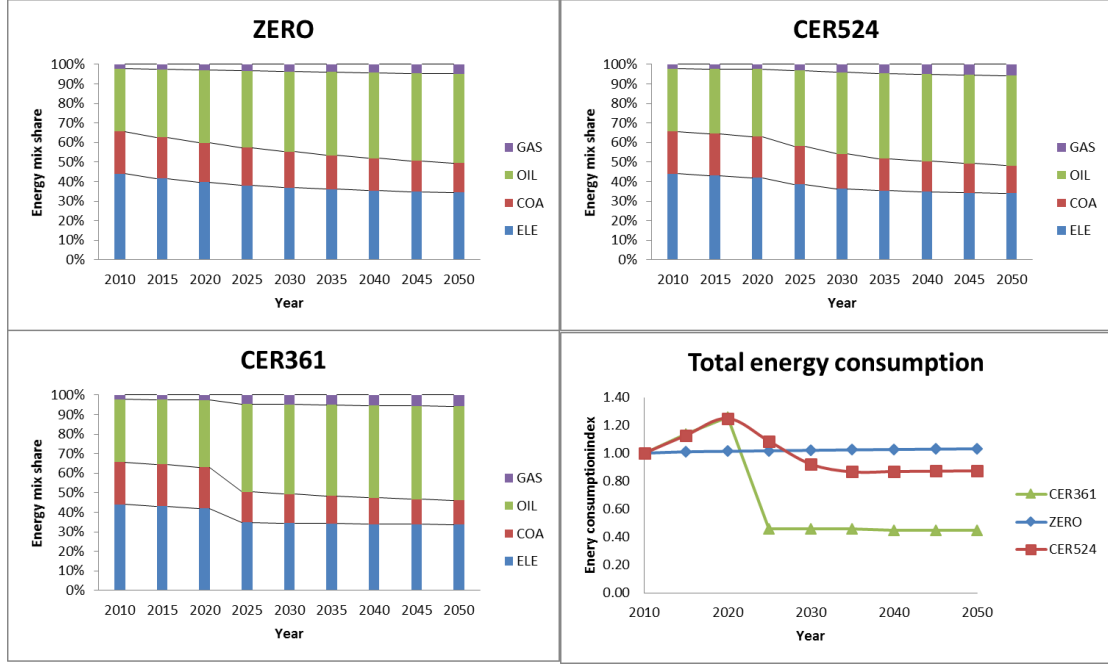


Figure 8: Change in energy mix in different policy scenarios

cess over time.²⁵ It is predicted to further climb to near 60% in 2020 and around 66% in 2030.²⁶ We explore the long-run effects of urbanization on sectoral growth in this section.

Depending on the region where one lives, people have different consumption bundle preferences, which are reflected by parameters in consumption equations.²⁷ The urbanization rate is exogenously given in the model for simplicity.²⁸ We assume the urbanization ratio increases to 60 percent in 2020 and continues to rise up to 66% in 2030 (hereafter *URB*). The rate of urbanization in 2050 will reach 78 percent, converging to current level of US.

When people move from rural to urban regions as predicted, total rural consumption growth declines from 4 percent to 1.10 percent in the reference case, while total growth of consumption in the cities increases to 4.36 percent. Data in

²⁵ According to the newly published 2009 City Development Report of China, an annual report conducted by China's Association of Mayors says that nearly 621.86 million people lived in cities in 2009. The number of cities grew from 132 at the beginning of 1949 to 655 by 2009.

²⁶ The world average urbanization ratio in developed countries 85%, and China's urbanization still lags behind the industrial development, which leaves huge room for further development.

²⁷ Explicitly, ζ in equation 13, β_{ne} in equation 14, ι in equation 15, and α_{coa} , α_{oil} , α_{gas} in equation 16 are distinguished between regions according to Input-output table data calibration.

²⁸ The government is expected to be careful when allocating fiscal spending as it carries out the new urbanization plans. One precondition for urbanization should be ensuring a sufficient and stable supply of agricultural produce, which will require improved efficiency in agricultural production, based on advanced technology and management. In addition, the provision of housing, social security and education for migrant workers and their children once they settle in the cities, will also present problems that must be solved during the urbanization process.

the base year show that people living in cities consume more than rural residents. Hence, welfare of the whole economy increases with the urbanization process (by 0.1 percent).

On the sector level, the agricultural sector (*agr*) shrinks relative to the reference case with an average growth rate of 3.78 percent. The construction sector (*con*) benefits from urbanization with an average growth rate of 4.17 percent. It is followed by the water supply industry (*wat*), with an average growth rate of 4.15 percent, and sectors which are important for city consumers grow, for instance, machinery (*mch*) and public services (*gse*). All four energy sectors (*ele*, *coa*, *oil*, *gas*) grow faster compared to the reference scenario, showing that city residents consume more energy goods or energy intensive goods compared to rural household. The increase in gas is higher than that of other energy sources.

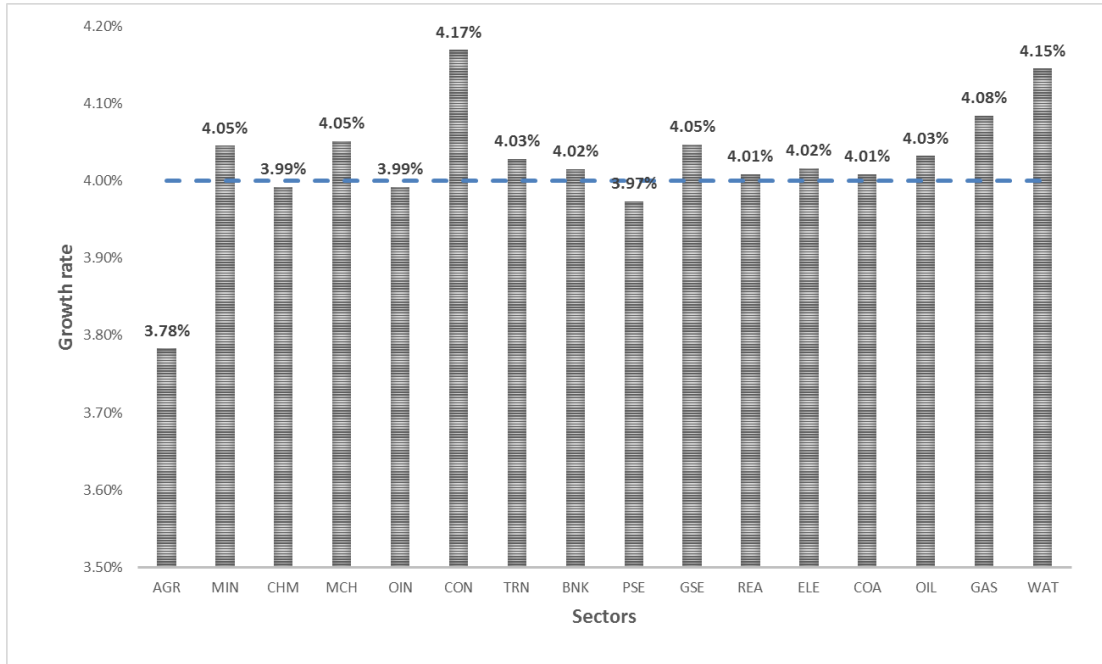


Figure 9: Growth rates of sectors with urbanization development

Table 6 provides the results when carbon policies (*CER524*, *CER361* and *ZERO*) are implemented in a growing economy with urbanization. As expected, the growth rate of consumption declines and the aggregate welfare loss rises when more stringent climate policies are implemented. Welfare losses in *ZERO*, *CER524*, *CER361* are 2.68%, 3.24% and 8.62%, respectively. The welfare losses are slightly higher compared to the scenarios without consideration of urbanization. This is due to the fact that urbanization increases the demand for energy

goods or energy intensive products.

Table 6: Consumption growth rate and welfare loss when climate policies are imposed

Scenario	Average emission per capita per year	Urban consumption growth rate	Rural consumption growth rate	Welfare change
URB	No carbon policy	4.36%	1.10%	+0.06%
ZERO	5.4t	4.16%	0.97%	-2.68%
CER524	5.24t	4.13%	0.95%	-3.24%
CER361	3.61t	3.87%	0.73%	-8.62%

Table 7: Growth rate of sectors in the long run (in %)

Sector	No urbanization			With urbanization		
	ZERO	CER524	CER361	ZERO	CER524	CER361
agr	4.15	4.17	4.17	3.92	3.94	3.93
min	1.54	1.16	-0.56	1.59	1.21	-0.49
chm	3.14	3.02	2.46	3.13	3.00	2.44
mch	2.92	2.78	2.18	2.98	2.84	2.24
oin	4.11	4.15	4.27	4.11	4.14	4.26
con	3.41	3.32	2.95	3.59	3.51	3.14
trn	3.13	3.01	2.44	3.15	3.02	2.45
bnk	3.64	3.60	3.42	3.65	3.62	3.43
pse	3.95	3.96	3.93	3.91	3.91	3.88
gse	3.93	3.91	3.70	3.98	3.96	3.74
rea	4.09	4.10	4.04	4.10	4.11	4.05
ele	-0.55	-1.00	-2.68	-0.56	-1.02	-2.69
coa	-1.22	-1.83	-4.15	-1.25	-1.86	-4.19
oil	0.74	0.29	-1.47	0.76	0.31	-1.44
gas	2.05	1.72	0.39	2.12	1.80	0.47
wat	2.81	2.67	2.08	2.92	2.77	2.16

Sectoral diversification follows the similar patterns as described in the last section. Energy intensive sectors decrease relatively more while labor capital intensive sectors are able to adjust and alleviate the effects of climate policies. When urbanization is taking place, sectoral growth changes slightly. As shown in Table 7, sectors which produce goods that are more demanded by urban household, such as *mch*, *con*, *gse*, *wat*, grow at a higher rate, while the growth rates of other sectors (e.g. *agr*) decline.

6 Conclusions

Using a multisector endogenous growth model, the paper derives the costs of carbon policies in China. We argue that growth dynamics constitute the crucial model element permitting reliable calculation of the effects. Intersectoral linkages and spillover effects are also important drivers of macroeconomic development.

Capturing the energy sector, with energy as an essential input to production in different sectors, in an accurate way is crucial for the results. More detailed modeling of the interaction between energy input and economic growth results in a more precise estimation of the cost of climate policies.

Our estimation results show that it is significantly easier for a growing economy to achieve stringent emission intensity reduction targets than absolute emission cuts. The welfare loss of achieving 40-45 percent emission intensity reduction in 2020 relative to the 2005 level is less than a half percent. Increasing the stringency of absolute emission targets and including a longer time horizon increases the cost of policies significantly. Welfare cost increase up to 8.3 percent depending on the stringency of the policy, if we assume the same kind of technical progress for the energy sectors as for the other sectors, constant energy prices in the reference case without policy, and a regular discount rate. This reveals that, even taking into account the ability of an economy to innovate and invest according to changing energy market conditions, costs of carbon policies cannot be disregarded when the reference growth rate is high. Of course, accelerated technology development in the energy sector, intensified learning effects, and increasing energy scarcities alleviate the costs of the climate policies. However, increasing urbanization acts in the opposite direction. The sectoral analysis reveals further interesting results. Central sectors in manufacturing such as machinery as well as electricity production have a very high carbon content in international comparison. Accordingly, increased investments to raise productivity associated with one unit of carbon emission have a very high return in the case of China, helping to decrease the cost of climate policies.

The overall assessment of climate policies in China has to include the benefits of reduced temperature rise, which is not treated in this paper. It would involve including important issues such as uncertainty, tipping points, and time lags in the carbon cycle. Nevertheless, we base our policy targets for the long run on an internationally shared carbon budget which appears to be within a realistic range. Provided that the net benefit of climate policy on a global scale is strongly positive, this suggests that also for a large country like China, climate policy is beneficial, provided it is based on a broad international agreement.

There are various possible extensions of our model. Various provinces in China

are very different in terms of income level, energy use, and economic structures. Hence, a multi-region setup would be helpful, to include provincial differences which are especially important when policies across regions are different. Moreover, an endogenous mechanism for the determination of urbanization and rural-urban migration could be included for further analysis. Extending the modeling of the electricity sector to include a comprehensive bottom-up model part for various generation technologies and transmission grid network could also be useful for energy studies.

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7 Appendix: sensitivity analysis on substitution elasticities

This section shows some sensitivity analysis on elasticity of substitutions used in the numerical model. We vary the value of Armington trade elasticities η and elasticity of substitution between energy sources in intermediate production. The results are shown in Table 8.

Table 8: Aggregate effects when varying elasticity of substitutions

Scenarios	Welfare change			Aggregate consumption growth		
Trade elasticity η	$\eta - 1$	η	$\eta + 1$	$\eta - 1$	η	$\eta + 1$
<i>CER524</i>	-3.20%	-3.10%	-3.00%	3.78%	3.79%	3.79%
<i>CER361</i>	-8.70%	-8.33%	-8.00%	3.52%	3.54%	3.55%
<i>ZERO</i>	-2.60%	-2.57%	-2.50%	3.81%	3.82%	3.82%
Energy Substitution σ_{egy}	$\sigma_{egy} = 0.1$	$\sigma_{egy} = 0.8$	$\sigma_{egy} = 1.5$	$\sigma_{egy} = 0.1$	$\sigma_{egy} = 0.8$	$\sigma_{egy} = 1.5$
<i>CER524</i>	-3.11%	-3.10%	-3.09%	3.78%	3.79%	3.79%
<i>CER361</i>	-8.38%	-8.33%	-8.29%	3.54%	3.54%	3.54%
<i>ZERO</i>	-2.57%	-2.57%	-2.57%	3.82%	3.82%	3.82%

As we expected, lowering trade elasticities makes it difficult to substitute between domestically produced goods and imported goods. That is, household consumption is more domestic dependent compared to higher values. As the prices of goods produced in home country are now relatively expensive because carbon policies increases the input price of energy, people now can buy less goods with the same amount of money. Moreover, consumers are not able to buy more imported goods as a substitute as the decline in trade elasticities. Hence, lowering trade elasticities results in higher welfare loss and lower consumption growth.

Energy substitution elasticity affects the intermediate production, and hence the final output. Lower value means all energy sources are not substitutable, while higher value suggests easy substitution between sources. It is obvious that higher substitution elasticity gives firms more flexibility in adapting to price change due to carbon policies, making it less costly to implementing emission reduction policies. On the contrary, lower substitution elasticity indicates the rigidity in changing production inputs, expensive sources are still heavily required for production. This leads to higher cost to implement carbon policy.

However, all these robustness check suggests that our cost estimation are stable

in magnitude. The results are not very sensitive to the elasticities. Of course, we can run analysis for all other elasticities. As from our experience, the above two are the most relevant to this paper.

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