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On the Economics of Climate Change and its Effects

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Economics

ON THE ECONOMICS OF CLIMATE CHANGE AND ITS EFFECTS

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by

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Abstract

This thesis consists of three separate papers; two examining the costs of climate change policy in developing economies and one studying the economic impacts of flooding.

In Chapter 2, I use a 2-sector non-balanced growth model to study the impact of structural change (the transition from industry to services) on carbon intensity. I calibrate the model to China and find that structural change plays an important role in reducing carbon intensity and lowering the economic cost of a carbon tax on GDP. For a 65% reduction target over 30 years, a $28/t carbon tax is needed and the output loss is 5.3% of GDP with structural change. Without structural change a $45/t tax is needed and 9.1% of GDP is lost. Rough calibrations to other developing countries show that structural composition matters as those with smaller service sectors can make emissions intensity reductions at lower cost.

In Chapter 3, we use a computable general equilibrium (CGE) model to study how a local economy responds to a flood and the subsequent recovery/reconstruction. Initial damage is modelled as a shock to the capital stock and recovery requires rebuilding that stock. We apply the model to Metro Vancouver by considering a flood scenario causing total capital damage of $14.6 billion spread across five municipalities. Transportation and Warehousing are most severely impacted, followed by Manufacturing and Wholesale Trade. Construction and Manufacturing play significant roles in the recovery. We find that the GDP loss relative to a scenario with no flood is 1.9% ($2.07B) in the first year after the flood, 1.7% ($1.97B) in the second year, 1.5% ($1.70B) in the fifth year and 1.1% ($1.42B) in the twentieth year.

In Chapter 4, I study how the composition of the energy sector and energy efficiency affect the cost of reducing carbon emissions. I show in the data that developing countries tend to be less energy efficient and have dirtier fuel mixes. I use an energy-economy model to study how GDP is affected by lowering emissions via a carbon tax. I find that developing countries face a larger decline in GDP from a carbon tax for an equivalent reduction in emissions, especially countries with a high dependence on coal. For example, China's level of GDP is reduced by 6.7% in the long-run compared to around 1% for all developed countries (for a 50% reduction in emissions). This is compounded by larger decreases in the growth *rate* in the short run for developing countries. Developing countries that have relatively low energy intensities and clean fuel mixes, like Brazil and Mexico, face considerably lower losses.

Keywords: Climate change economics, structural change, flooding, reconstruction, economic development, energy economics

Co-Authorship Statement

The following thesis contains material co-authored by Professor James Davies. We are equally responsible for the work which appears in Chapter 3 of this thesis.

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A.B. Gertz May 3, 2015
Chicago, Illinois

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Chapter 1

Introduction

This thesis consists of three chapters which examine topics related to climate change. Chapters 2 and 4 examine macro policy questions related to the cost of implementing climate policy in developing countries. More specifically, these chapters study how the costs of climate policy are affected by the industrial composition (structural change) and the energy/carbon intensity.[1] Chapter 3, which is joint work with Jim Davies, builds a framework to study the economic impacts of flooding on a city. Climate change is expected to cause increased flooding and this work enables improved assessments of the cost of flooding which can be compared to adaptation measures like relocation and diking. The three chapters also share the common thread of using multi-sector growth models to study macro-environment issues.

While limiting emissions by developing countries is recognized as essential, some argue developing countries cannot make significant GHG reductions without doing serious harm to their economic development. The basis for this argument is that developing economies are more carbon intensive than developed economies. That is, developing countries emit more carbon (burn more fossil fuels) to produce a unit of GDP, making it more costly to implement policies to cut back emissions (this claim is examined in detail in Chapter 4). One important aspect that this argument neglects is structural change - that is, the tendency for the service sector share to rise as the economy grows (with the service sector being relatively less energy intensive).

In Chapter 2, I study how the growth of the service sector relative to industry - structural change - impacts carbon emissions intensity. Consider an economy aggregated to the 2-sector level, industry and services. If services are less carbon-intensive than industry, an increase in the service share of total output will lower the carbon intensity of the overall economy. In addition, the intensity of the overall economy can also drop as a result of one or both sectors becoming more carbon-efficient. I quantitatively assess the importance of structural change

[1] Energy consumed or carbon emitted per unit of GDP.

in lowering carbon intensity relative to sectoral efficiency gains. I also examine the structural change-induced cost savings of hitting various emissions intensity reduction targets via a carbon tax. This is key for developing countries because they have smaller service sectors and thus more opportunity for structural change going forward.

To tackle these questions I develop a 2-sector non-balanced growth model. The industry and service sectors each use capital, labour and fossil fuels as inputs to production. Fossil fuels generate carbon emissions with industry being more energy (and emissions) intensive. One sector can grow more rapidly than the other and dominate asymptotically, depending on parameter values. The model incorporates three mechanisms that can lower carbon intensity:

1. Substitution of services (low carbon) for industry (high carbon);

2. Substitution of value added for fossil fuels at the sectoral level;

3. Total factor productivity growth at the sectoral level.

The novel contribution of this study is to quantify the importance of the first mechanism - the transition from industry to services. As the less emissions-intensive service sector's share of output grows, the overall carbon intensity of the economy decreases (e.g. more office parks and fewer steel mills).

I quantitatively assess the importance of structural change in lowering carbon intensity in China. I choose China because it is the world's largest emitter of carbon and has a relatively small but growing service sector. I calibrate the model to the Chinese economy in 2007 and simulate it going forward (primarily focusing on a 30-year time horizon). I compare how the rate of structural change, determined by a parameter in the model, impacts carbon intensity. I then introduce a carbon tax, which lowers GDP, and quantify how the loss of GDP is affected by the rate of structural change.

I find that with *no carbon tax or other climate policy*, using conservative parameter values, aggregate emissions intensity in China falls by more than 27% after 30 years, with structural change accounting for nearly 1/2 of that reduction. A carbon tax is introduced to achieve even greater emissions reductions, which lowers GDP.[2] The reduction in GDP is nearly halved by accounting for structural change. I also compare the reduction in carbon intensity resulting from structural change (without a carbon tax) across countries. To do this I perform "rough calibrations" of the model to other developing economies and simulate the model. I find that the emissions intensity reductions are much greater in countries with smaller service sectors. This implies that those countries can make emission reductions at lower cost because they have

[2] I do not account for the economic benefits of avoiding climate change. See Chapter 2 for an explanation.

more scope for structural change. This has significant implications in terms of where resources and attention should be focused to mitigate future emissions as emerging economies develop.

Climate change is expected to lead to increased frequency and severity of extreme weather events such as flooding. Chapter 3 develops a framework for determining the economic costs associated with flooding events. Floods cause physical damage to capital, such as homes, buildings, equipment and infrastructure. In turn, this damage diminishes the available inputs to production resulting in lost economic output. This effect reverberates throughout the entire economy via linkages. For example, if a computer chip manufacturer has its output halved as a result of damaged equipment it will not be able to satisfy all of its orders. Consequently, a cellphone maker who had no damage from the flood may see a drop in output due to a shortage of inputs (and may have to pay higher prices for those inputs). Furthermore incomes will be reduced leading to a decrease in consumption and savings of households. This can further impact trade and government revenues.

To examine the impact of a flood in a city and the subsequent recovery, we develop a dynamic multi-sector computable general equilibrium (CGE) model. In the absence of a flood, the economy follows the balanced growth path (all quantities and prices increase at constant rates). The flood is modelled as a shock to the capital stocks of firms in the economy. After the flood, the economy rebuilds the capital stock through investment and converges back toward the balanced growth path over time. We compare the economic output under the flood and no-flood scenarios to determine the economic impacts of the flood.

As an application of the model we consider a flood of Metro Vancouver.[3] It is located on land that includes the delta of the Fraser River. About 20% of the population and considerable economic activity are located in the flood plain, and are protected by dikes. In order to calibrate the model to Metro Vancouver and simulate the economy over a forward time horizon, we require a local input-output table (and final demand table) to account for linkages across industries. One contribution of the paper is to build the local input-output table from the provincial British Columbia table and local employment data. This includes estimates of intra-provincial trade between Metro Vancouver and the rest of the province.

Our flood scenario of the lower Fraser Valley causes total capital damage of $14.6 billion in our baseline scenario. We allocate the damage across sectors by noting the employment distribution of the municipalities hit by flood relative to the region as a whole. The Transportation and Warehousing sector is most exposed in percentage terms because the airport and the region's largest seaport are located in the flood plain. The Manufacturing and Wholesale Trade sectors are also hit proportionally hard. Construction and Manufacturing, the two most impor-

[3]This work is part of the Coastal Cities at Risk Project which is an interdisciplinary study of flooding in Vancouver, Manila, Bangkok and Lagos.

tant sectors for producing investment goods, recover rapidly. Transportation and Warehousing, the most damaged sector, also recovers rapidly. Meanwhile, Finance and Real Estate actually sees a relative *decrease* in its capital stock. This occurs in the most capital-intensive industries after the flood damage because their marginal product of capital becomes smaller than other industries and thus there is little investment in capital-intensive industries. The biggest adjustment occurs in the first year after the flood followed by a steady re-convergence toward balanced growth.

In Chapter 4, I return to the topic of climate policy and developing countries. As mentioned above, many argue that it will be more costly for developing countries to reduce emissions because their economies tend to be less energy efficient and they tend to have more carbon-intensive fuel mixes (in particular a preponderance of coal). While I showed in Chapter 2 that structural change may mitigate the cost of lowering emissions in many developing countries, there is still a question of whether the energy economies of developing countries drive costs materially higher in the first place. If not, it could actually be *cheaper* for developing countries to reduce emissions relative to developed countries.

I document facts about energy consumption across countries and over time. In general, more developed economies are more energy efficient and total energy consumption has plateaued in many developed countries. Meanwhile, energy consumption is rising rapidly is most developing economies. There is more variation across all countries in the fuel mix. These variations are driven by geography (access to resources, climate) and policy (degree of support for nuclear power and renewables).

I use an energy-economy model to study how GDP is affected by lowering emissions via a carbon tax. I compare losses across countries to see if developing countries face much steeper losses than developed countries. My model is based on the neoclassical growth structure. A final good producing firm uses capital, energy services and labour as inputs. Energy services is a composite of "clean" and "dirty" energies, which are aggregated using a CES function. CO_2 emissions are a product of the dirty energy sector.

I calibrate and simulate the model for six developing countries and six developed countries. Dirty energy is taxed such that there is an equivalent reduction in emissions intensity across countries. The GDP loss as a result of the tax is compared across countries. I find that the countries with the largest proportion of coal power face the greatest loss of output from lowering emissions (China, India and South Africa). Their costs of reducing emissions are considerably higher than those of developed countries; however, developing countries that are relatively energy efficient, like Brazil and Mexico, experience losses that are more in line with developed countries.

Chapter 2

Structural change and climate policy in developing countries

Industrialized countries are responsible for the majority of historical carbon emissions as a result of higher energy consumption. However, developing economies are now among the highest emitters on a current annual basis. In fact, China is now the world leader in carbon emissions and it is widely agreed that rapidly-growing developing countries will be the major source of future emissions (see table 2.1). To keep greenhouse gas (GHG) concentrations within safe levels, developing countries must significantly reduce emissions compared to a business-as-usual scenario (Stern, 2007).

While limiting emissions by developing countries is recognized as essential, some argue developing countries cannot make significant GHG reductions without doing serious harm to their economic development. The basis for this argument is that developing economies are much more carbon intensive than developed economies (see Chapter 4). That is, developing countries emit more carbon (burn more fossil fuels) to produce a unit of GDP, making it more costly to implement policies to cut back emissions. One important aspect that this argument neglects is structural change - that is, the tendency for the service sector share to rise as the economy grows.[1] Structural change could be very important for climate change because services are less carbon-intensive than industry (in section 2.5.1, I show the share of fossil fuels in production for China is 0.10 for industry, compared to 0.08 for services).

In this paper I study how the dynamic process of structural change impacts the time path of carbon emissions intensity. Consider an economy aggregated to the 2-sector level, industry and services. If services are less carbon-intensive than industry, an increase in the service share of total output will lower the carbon intensity of the overall economy. However, the

[1] See Kuznets (1957) for an early examination of structural change in the U.S. For a more recent cross-country study see Duarte and Restuccia (2010).

intensity of the overall economy can also drop as a result of one or both sectors becoming more carbon-efficient. These efficiency gains could occur as a result of more efficient technology or processes, a change in the fuel mix toward clean energy, or intra-sectoral structural change favouring less carbon-intensive sub-sectors. To shed light on the relative importance of these mechanisms, I quantitatively assess the importance of structural change in lowering carbon intensity relative to sectoral efficiency gains. Next, I examine the structural change-induced cost savings of hitting various emissions intensity reduction targets via a carbon tax. This is key for developing countries because they have smaller service sectors and thus more scope for structural change going forward. I also examine the impact of the carbon tax time path to determine whether it is better to have an initially low tax that increases over time or a constant tax that begins at a higher level.

To tackle these questions I develop a 2-sector non-balanced growth model that builds on Acemoglu and Guerrieri (2008). The industry and service sectors each use capital, labour and fossil fuels as inputs to production. Fossil fuels, supplied at an exogenously specified price, generate carbon emissions with industry being more energy (and emissions) intensive. Each sector's growth rate is determined by the input growth rates combined with the conditional demand for those inputs, and the exogenous total factor productivity (TFP) growth rate. One sector can grow more rapidly than the other and dominate asymptotically, depending on parameter values. To match the historical trend of a growing service sector, I consider parameter values where the service sector grows more rapidly than industry. The two goods are combined into a final good that the representative household can choose to consume or invest.

The model features three mechanisms that can lower carbon intensity:

1. Substitution of services (low carbon) for industry (high carbon);

2. Substitution of value added for fossil fuels at the sectoral level;

3. Total factor productivity growth at the sectoral level.

The novel contribution of this paper is to quantify the importance of the first mechanism – the transition from industry to services. As the less emissions-intensive service sector's share of output grows, the overall carbon intensity of the economy decreases (e.g. more office parks and fewer steel mills).

The other mechanisms can be interpreted as efficiency gains via new machines or processes (e.g. more green energy or energy efficient machines) or intra-sectoral structural change (e.g. less cement production in favour of consumer electronics). In the model, a carbon tax increases the effective price of fossil fuels, which induces both sectors to use fewer fossil fuels. It also drives up the price of the more carbon-intensive industrial goods relative to services. This can lead to additional substitution toward services.[2]

To validate the model, I calibrate it to the U.S. in 1951. For appropriate elasticity parameters, the model roughly matches the rate of structural change from industry to services up to the 1980s and the decrease in fossil fuel intensity up to the mid 1970s.

To quantitatively assess the importance of structural change in lowering carbon intensity in a developing country, I calibrate the model to the Chinese economy. I choose China for the numerical exercise because it is a developing country with a relatively small service sector and it is the global leader in GHG emissions. I find that with *no carbon tax or other climate policy*, using conservative parameter values, aggregate emissions intensity in China falls by more than 27% after 30 years, with structural change accounting for nearly 1/2 of that reduction. Next, a carbon tax is introduced such that an emissions intensity reduction target is met. In the baseline scenario with structural change, emissions intensity can be reduced by 65% over 30 years with a $28/t carbon tax; the cost is 5.3% of GDP. To achieve the same target with a 1-sector model a $45/t tax is needed which costs 9.1% of GDP. This difference is because in the 1-sector model, the more carbon-intensive industrial sector does not shrink relative the the aggregate economy. However, these results depend to an extent on the elasticity of substitution between fossil fuels and value added. For small values of this elasticity, it is very cheap to reduce emissions intensity and structural change becomes less important.

I also consider different time paths for the carbon tax to test if it is better to implement a high carbon tax quickly or ramp up the tax more slowly. A tax beginning at $7/t and ramping up at 5% per year can deliver the same 65% intensity reduction in 30 years but at a cost of only 3.5% of GDP. This is because with a ramped up tax, the economy has time to build up the capital stock (and population) as a response to deal with the eventual higher cost of energy.

I perform rough calibrations of the model to other developing economies and run simulations with no carbon tax to compare their emissions intensity reductions in 30 years time. The countries with the smallest service sectors today (China and Indonesia) make significantly greater intensity reductions (27% and 30%, respectively) than those with larger service sectors (10% to 20%).

There are a couple of key new implications of these findings. First, any cost-benefit analysis of climate policy that does not properly account for structural change may considerably overestimate the cost of that policy. This could be important for developing countries considering implementing new climate policy and informing treaty negotiation strategies for all countries.

[2]There is no climate feedback on the economy in this model, thus only the cost side of a carbon tax is captured. This is a reasonable abstraction since emissions accrue to the entire world and the model considers a single country. It is also consistent with the literature studying climate policy impacts on a single country.

Second, this result implies that in order to mitigate climate change it may be important to focus relatively more effort on reducing emissions in developing countries other than China. For example, India and South Africa have larger service sectors than China and may have more difficulty reducing emissions.

Modelling structural change dates to Baumol (1967), who used labour productivity differences to drive structural change.[3] Kongsamut et al. (2001) used non-homothetic preferences to achieve structural change from the demand side. The rationale is explained as needing a minimum amount of agricultural products to survive; only after that amount is met can income be spent on other types of goods. However, it is less clear if the same logic can apply for a switch to services from industry.[4] Since service shares in consumption and production are similar, there is no clear advantage of a demand-driven approach over a supply-driven approach. Ngai and Pissarides (2007) generalized structural change to n sectors driven by supply side TFP growth rate differences. However it is not possible to get structural change in both real and nominal terms given observed TFP growth rate differences across sectors.[5] I follow the supply-side approach of Acemoglu and Guerrieri (2008) because TFP growth rate differences, such as in Ngai and Pissarides (2007), are not needed. Their model accurately replicated the evolution of capital-intensive and non-capital intensive sectors of the U.S. economy and China's service sector is much more capital-intensive than industry. The model is extended herein by adding fossil fuels as an input and adopting a nested CES structure. This is the first paper to use a model of structural change to study an environmental issue: calibrating the more detailed model to China, plus rough calibrations to other countries, allows for studying the relationship between structural change and carbon emissions. Furthermore, adding a carbon tax to the model enables me to study how the pace of structural change responds *endogenously* to the tax.

Numerous studies of climate change policy have been carried out at the global and national levels. Nordhaus (1994) pioneered work on the economics of climate change with a global, 1-sector model called DICE. Other models, recognizing the importance of cross-country heterogeneity, added multiple regions but still featured one sector (e.g. Nordhaus and Yang, 1996; Plambeck and Hope, 1996). Recognizing the importance of the sectoral composition of the economy to carbon emissions, other studies of climate policy used multi-region, multi-sector CGE models like Whalley and Wigle (1991), Babiker et al. (2000), Paltsev et al. (2007) and Schinko (2010). There have also been many CGE studies of climate policy focused specifically on China including Zhang (1998) and Dai et al. (2011), who quantified the cost of reducing

[3] Empirical work on structural change and its impact on carbon emissions and energy consumption will be covered in section 2.1.

[4] Furthermore, this approach fixes good prices in time as a function of preference parameters which is difficult to support in the data.

[5] Manufacturing productivity growth is greater than services.

emissions in China. Paltsev et al. (2012) examined China's role in mitigating climate change by incorporating a global CGE model into an integrated assessment model which determines actual climate change based on the output of carbon emissions. For CGE models that account for structural change in their baseline (e.g., see the EPPA model, Paltsev et al., 2005), it is typically done by changing consumption share parameters over time.[6] This approach makes the household behaviour more complicated and introduces many more degrees of freedom to the parameter space which generates additional uncertainty around the results.

This paper is the first to isolate and address the role of structural change from industry to services in reducing future carbon emissions, and that role turns out be quantitatively important. In addition to showing the important role of structural change in reducing emissions intensity, this paper shows the endogenous dynamic structural change response to a carbon tax which has not previously been done. This has implications for how carefully other studies should treat the structural change issue and serves as a reference point for assessing whether structural change effects are being adequately captured in large CGE models. While the focus of the simulations in this paper is for China, the findings could be applied to any country or region.

The paper is organized as follows. Section 2.1 discusses data on carbon emissions and the service sector, section 2.2 presents the model and section 2.3 describes the characterization of the solution to the model. Section 2.4 tests the quantitative ability of the mode to match key moments by simulating the U.S. economy. Section 2.5 details the forward-looking numerical experiments and section 2.6 offers a discussion of the results.

2.1 Emissions and the service sector

Most carbon emissions in the atmosphere result from the burning of fossil fuels in industrial processes (including power generation). Since CO_2 emissions remain in the atmosphere for roughly 100 years, developed countries are responsible for a majority of the emissions currently in the atmosphere. However, lowering or stabilizing atmospheric concentrations depends on slowing current and future emissions.[7] Table 2.1 shows that some developing countries are already among the world leaders in emissions, and assuming a continued faster growth rate, their share of emissions will increase.

Developing countries are much more carbon intensive than developed countries (see table 2.1). A smaller service sector is one reason for the higher intensities, although those countries generally also have dirtier fuel mixes (i.e. more coal) and are less energy efficient than

[6] Another approach is to use sector-specific productivity growth rates, but the growth rates needed are generally not supported by data.

[7] There has been discussion of technologies to remove carbon from the atmosphere, however those technologies are far from the stage of implementation.

developed countries when performing the same tasks. Calculations associated with the model calibration (detailed in section 2.5.1) show that the service sector contributes 18% of China's emissions, while industry contributes 82%. Thus if China's service share was 79%, the level of the U.S., its emissions would be 36.5% lower at $4,881 \times 10^3$ kt. Thus the gap in emissions between the U.S. and China is more than accounted for by the difference in sectoral compositions. However, China's sectoral intensities are higher and its economy is growing more rapidly, thus even with a larger service sector its emissions would blow past those of the U.S. over time.

	CO_2 Emissions (kt)	2011 GDP growth	CO_2 Intensity (kg per USD)	Service share
China	7,687,114	9.3%	0.93	43%
India	1,979,425	6.3%	0.58	55%
Russia	1,574,386	4.3%	0.81	62%
South Africa	499,016	3.1%	1.08	66%
United States	5,299,563	1.7%	0.42	79%
European Union	3,617,580	1.5%	0.27	74%
Japan	1,101,134	-0.7%	0.29	73%
Australia	400,194	1.9%	0.54	76%

Table 2.1: 2009 emissions, intensity and service share. Source: World Bank (n.d.).

The experience of the United States suggests that the importance of structural change in lowering energy intensity (and correspondingly carbon intensity) potentially depends on the stage of development, energy prices and technological change. The service sector share has been steadily growing in the U.S. while the energy (and carbon) intensities have been declining. Figure 2.1 shows the CO_2 intensity and service sector share of the United States since 1951. The service sector grows steadily between 1951 and about 1980, then grows at a much faster pace until 1990, and then finally the pace slows again until the present day. The rapid transition during the 1980s comes at a time of decline in U.S. manufacturing and increased computerization and automation.

The energy intensity is decreasing while the service share is increasing. The sharpest decline in intensity occurs in the mid-1970s and early 1980s. This change in regime is associated with the energy price shocks of the 70s and early 80s. Popp (2002) found that the high energy prices were important in inducing technical change. Correspondingly, empirical studies by Schipper et al. (1990) and Rose and Chen (1991) found that sectoral efficiency gains, or technological progress, was the dominant mechanism for reducing energy intensity after the 1970s. However, Wing (2008) found that from 1958 to 2000, structural change was responsible for nearly 2/3 of the reduction in energy intensity in the U.S., with the caveat that efficiency gains dominate after 1973 (the year of the first OPEC oil price shock). If energy prices do not spike in the coming decades, it is reasonable to assume that structural change will play a more important role in reducing carbon intensity for currently developing countries than it did for the United States.

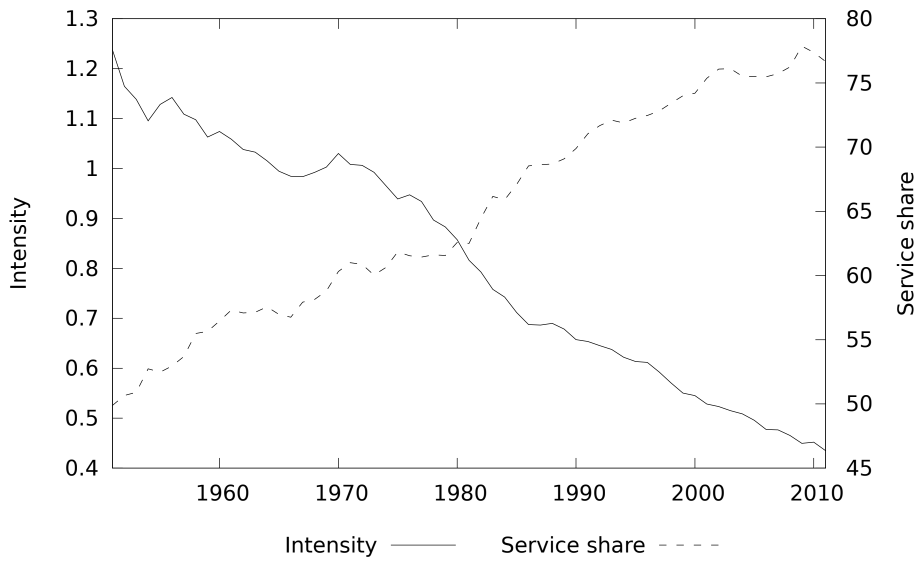

Figure 2.1: U.S. CO_2 intensity declines over time, service sector share of GDP increases.

Studies on the impact of structural change on energy intensity for other countries have come to broadly similar conclusions. Gardner (1993) examined Ontario industry between 1962 and 1984 and found structural change to be equally as important as efficiency gains. Diakoulaki and Mandaraka (2007) examined the impact of structural change on total carbon emissions for countries in Europe between 1990 and 2003 and found an important role for structural change. There have been a few studies about energy intensity and structural change in China, although typically for small time windows. Fisher-Vanden et al. (2004) found that sectoral shifts accounted for 17.6% of the decrease in energy intensity from 1997-1999. Liao et al. (2007) found that the energy intensity increase from 2003-2005 was driven by the expansion of high-energy sub-sectors of the economy.[8] In summary, structural change has been observed to lower energy (and carbon) intensity across countries over different periods of time. This paper examines the potential role for structural change in lowering carbon intensity over the coming decades in developing countries.

[8]This brief increase was a blip on an otherwise decreasing trend.

2.2 Model Environment

The economy is a 2-sector non-balanced growth model where one sector represents industry and the other services. The model is non-balanced in the sense that the two sectors have different constant long-run growth rates, however the aggregate economy performs like a balanced growth model.[9] Goods produced by each sector are aggregated into a final consumption/investment good. Each sector uses labour, capital and fossil fuels as inputs to production. The fossil fuels emit carbon (that can be taxed). Consumers maximize utility by choosing consumption and investment.

The production function for each sector has the same functional form but the parameters may differ which allows for differences in the growth rates and emissions intensities. I will impose parameter restrictions which force the service sector to grow faster than industry.

2.2.1 Production

The intermediate goods are combined using a CES function to produce a final good:

$$Y(t) = [\gamma Y_I(t)^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma)Y_S(t)^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \tag{2.1}$$

Here, $Y(t)$ is the final good output at time t, $Y_I(t)$ is the industrial intermediate, $Y_S(t)$ is the services intermediate, γ is a share parameter and ϵ is the elasticity of substitution between industrial goods and services. The resource constraint is given by:

$$\dot{K}(t) + \delta K(t) + C(t) = Y(t) \tag{2.2}$$

Here, $K(t)$ is the capital stock, $C(t)$ is consumption and δ is depreciation.

Intermediate goods

Intermediates are also produced using a CES function:

$$Y_i(t) = A_i(t)[\gamma_i F_i(t)^{\frac{\epsilon_i-1}{\epsilon_i}} + (1-\gamma_i)VA_i(t)^{\frac{\epsilon_i-1}{\epsilon_i}}]^{\frac{\epsilon_i}{\epsilon_i-1}},\ i \in (I,S) \tag{2.3}$$

$$VA_i(t) = K_i(t)^{\alpha_i} L_i(t)^{1-\alpha_i} \tag{2.4}$$

$F_i(t)$ is fossil fuels demanded and $VA_i(t)$ is value added demanded at time t in sector i, where $L_i(t)$ is labour. $A_i(t)$ is the total factor productivity, α_i and γ_i are share parameters and ϵ_i is the elasticity of substitution between fossil fuels and value added. Fossil fuels are supplied at an

[9]Constant long-run growth rates in consumption, output, capital stock; constant interest rate.

exogenously set price; this can be thought of as an unlimited endowment which has a fixed cost of production.[10]

The profit function for the intermediates is:

$$\pi_i(t) = p_i(t)Y_i(t) - p_i^F(t)F_i(t) - R(t)K_i(t) - w(t)L_i(t) - \tau(t)Z_i(t) \tag{2.5}$$

Here, $p_i(t)$ is the price of good i, $p_i^F(t)$ is the price of fossil fuels for sector i, $R(t)$ is the rental rate of capital, $w(t)$ is the wage, $\tau(t)$ is the carbon tax and $Z_i(t)$ are emissions generated in production.[11] Emissions are generated by the use of fossil fuels, so $Z_i(t) = \frac{1}{\phi_i}F_i(t)$ where $\frac{1}{\phi_i}$ is the carbon emitted per unit of energy generated in sector i. As a result, the production and profit functions can be simplified:

$$Y_i(t) = B_i(t)[\gamma_i' Z_i(t)^{\frac{\epsilon_i - 1}{\epsilon_i}} + (1-\gamma_i')VA_i(t)^{\frac{\epsilon_i - 1}{\epsilon_i}}]^{\frac{\epsilon_i}{\epsilon_i - 1}} \tag{2.6}$$

$$\pi_i(t) = p_i(t)Y_i(t) - (p_i^F(t)\phi_i + \tau(t))Z_i(t) - R(t)K_i(t) - w(t)L_i(t) \tag{2.7}$$

Fossil fuels could be omitted altogether in the formulation of the model, skipping directly to carbon emissions as an input. Although this would be consistent with environmental literature (e.g. Copeland and Taylor, 2005), the specification above makes the calibration exercise more intuitive. It may seem that because the relationship between emissions and fossil fuels is constant in time there is no scope for substitution between different fossil fuels. However, this can be interpreted in the model as a substitution of value added for fossil fuels since new capital would be needed to use a different fuel in the production process. In fact, any substitution toward more energy efficient machines or processes, or within-sector structural change toward less carbon-intensive activities can be interpreted as substituting away from fossil fuels toward value added in that sector. This would include oil and gas power plants, green energy, more energy efficient machines and buildings, and intra-sectoral shifts such as light manufacturing for heavy industry. Note that efficiency gains also occur via growth in the total factor productivity term, $B_i(t)$.

[10]Fossil fuels could also be interpreted as having a global market where prices are not impacted by domestic demand, however the revenues from fossil fuels are paid to the domestic household.

[11]Each sector can have a different price of fossil fuels due to differing mixes of coal, oil and gas. The price of capital and wages are the same across sectors, as is the carbon tax.

2.2.2 Household

Household preferences are represented by

$$\int_0^\infty \exp(-(\rho - n)t)\frac{c(t)^{1-\theta} - 1}{1-\theta}dt, \tag{2.8}$$

where ρ is the discount rate, n is population growth, $c(t)$ is per capita consumption and $1/\theta$ is the intertemporal elasticity of substitution. Households have an initial endowment of capital, $K_0 > 0$, and an endowment of labour $L(t)$ which grows exogenously and is supplied inelastically.

The law of motion of capital is given by:

$$\dot{K}(t) = r(t)K(t) + w(t)L(t) + p^Z(t)Z(t) - c(t)L(t) \tag{2.9}$$

Here, $r(t) = R(t) - \delta$ is the interest rate, $w(t)$ is the wage, and $p^Z(t)$ is the average price of emissions. Note that the household receives a lump-sum payment for the right to emit carbon (or use fossil fuels). The household problem gives the following standard Euler equation:

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\theta}(r(t) - \rho) \tag{2.10}$$

The transversality condition ensures that investment does not dominate consumption asymptotically:

$$\lim_{t\to\infty}\left[K(t)\exp\left(-\int_0^t r(\tau)d\tau\right)\right] = 0 \tag{2.11}$$

2.2.3 Equilibrium

A competitive equilibrium is a path of factor and intermediate good prices $[R(t), w(t), p_I^Z(t), p_S^Z(t), p_I^{VA}(t), p_S^{VA}(t), p_I(t), p_S(t)]_{t\geq 0}$; emissions, value added, capital and employment allocations $[Z_I(t), Z_S(t), VA_I(t), VA_S(t), K_I(t), K_S(t), L_I(t), L_S(t)]_{t\geq 0}$ such that given prices firms maximize profits and markets clear; and consumption and investment $[c(t), \dot{K}(t)]_{t\geq 0}$ that maximize representative household utility given prices and initial capital stock K_0. Solving the competitive equilibrium yields the following price equations:

$$\begin{aligned} R(t) &= \alpha_i \frac{p_i^{VA}(t)VA_i(t)}{K_i(t)} \\ w(t) &= (1-\alpha_i)\frac{p_i^{VA}(t)VA_i(t)}{L_i(t)} \\ p_i^Z(t) &= \gamma_i' B(t)^{\frac{\epsilon_i - 1}{\epsilon_i}} p_i(t)\left(\frac{Y_i(t)}{Z_i(t)}\right)^{1/\epsilon_i} \end{aligned} \tag{2.12}$$

$$
\begin{aligned}
p_i^{VA}(t) &= (1-\gamma_i')B(t)^{\frac{\epsilon_i-1}{\epsilon_i}} p_i(t)\left(\frac{Y_i(t)}{VA_i(t)}\right)^{1/\epsilon_i} \\
p_i(t) &= \omega_i\left(\frac{Y(t)}{Y_i(t)}\right)^{1/\epsilon}
\end{aligned}
$$

Here, $\omega_I = \gamma$, $\omega_S = 1-\gamma$ and the final good is the numeraire. Market clearing for the inputs is given by:

$$
\begin{aligned}
K(t) &= K_I(t) + K_S(t) \\
L(t) &= L_I(t) + L_S(t) \\
Z(t) &= Z_I(t) + Z_S(t)
\end{aligned} \tag{2.13}
$$

2.3 Characterizing the solution

The model exhibits asymptotic stability, which is to say all quantities and prices have constant asymptotic growth rates. Since the two sectors have different growth rates, one will asymptotically dominate the other. However, both sectors continue to grow even if one becomes relatively tiny.

As in Acemoglu and Guerrieri (2008), a constant growth path (CGP) is defined such that the growth rate of per capita consumption is asymptotically constant.[12]

$$
\lim_{t\to\infty}\frac{\dot{c}(t)}{c(t)} = g_c^* = g_C^* - n \tag{2.14}
$$

By equation (2.10), this implies an asymptotically constant interest rate. Furthermore, the final good must grow at the rate of consumption, $g^* = g_C^*$, otherwise the transversality condition is violated. Differentiating (2.1), the growth rate of the final good is obtained:

$$
g(t) = \frac{\dot{Y}(t)}{Y(t)} = \frac{\gamma Y_I(t)^{\frac{\epsilon-1}{\epsilon}} g_I(t) + (1-\gamma)Y_S(t)^{\frac{\epsilon-1}{\epsilon}} g_S(t)}{\gamma Y_I(t)^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma)Y_S(t)^{\frac{\epsilon-1}{\epsilon}}} \tag{2.15}
$$

Thus, the final good asymptotic growth rate, g^*, is equal to the the minimum ($\epsilon < 1$) or maximum ($\epsilon > 1$) of the sectoral growth rates (g_I^*, g_S^*). In order to be consistent with the stylized fact that the service sector increases its share of output with time, I impose $g_S^* > g_I^*$ and $\epsilon > 1$.

Since the sectoral production functions are CES, the sectoral growth rates are derived similarly to the final good (except there is also TFP growth to include). As a result, there are four

[12]Acemoglu and Guerrieri (2008) show the saddle-path stability of their model which implies the equilibrium solution converges to the unique CGP.

cases to consider when solving for the remaining growth rates; two for each sector[13]:

$$g_i^* = \begin{cases} a_i + g_{VA_i} \text{ if } \frac{VA_i}{Z_i} \to 0 \text{ and } \epsilon_i < 1 \\ a_i + g_{Z_i} \text{ if } \frac{VA_i}{Z_i} \to \infty \text{ and } \epsilon_i < 1 \end{cases} \tag{2.16}$$

All of the sectoral asymptotic growth rates can be calculated using the result that $g_S^* = g^*$ plus equations (2.4), (2.12), (2.13) and (2.16). The asymptotic growth of the rate of return on capital is 0 (in both sectors) and the growth rate of the wage is the same in both sectors. The market clearing conditions imply that the growth rate of an aggregate input grows at the rate of that input in the sector which is using that input at a faster-growing rate. For example, if $n_S^* > n_I^*$ then $n_S^* = n$. Otherwise $n_I^* = n$.

Below I give the resulting asymptotic growth rates for the case in which $\frac{VA_i}{Z_i} \to 0$ in both industries. This solution is the case of the numerical work shown later in the paper.

$$\begin{aligned}
g_S^* &= g^* = g_C^* \\
n_S^* &= n \\
g_{K_S}^* &= g_K^* = g^* \\
g_{Z_S}^* &= (\epsilon_S - 1)a_S + g^* - \epsilon_S g_{p_S^Z} \\
g_I^* &= g_S + \frac{\epsilon}{1-\alpha_S}[(1-\alpha_S)a_I - (1-\alpha_I)a_S] \\
n_I^* &= n_S^* + \frac{\epsilon - 1}{\epsilon}(g_I^* - g_S^*) \\
g_{K_I}^* &= g_{K_S}^* + (n_I^* - n_S^*) \\
g_{Z_I}^* &= g_{Z_S}^* + \frac{1}{1-\alpha_S}\{(\epsilon - 1)(1-\alpha_S)a_I + [(1-\epsilon_S)(1-\alpha_S) \\
&\quad +(\epsilon_I - \epsilon)(1-\alpha_I)]a_S\} - \epsilon_I g_{p_I^Z} + \epsilon_S g_{p_S^Z}
\end{aligned}$$

Note that $\epsilon > 0$, $\alpha_S > \alpha_I$ and $a_S = a_I$ (as in numerical exercise) implies $g_S^* > g_I^*$ as required. Furthermore, $n_S^* > n_I^*$ and $g_{K_S}^* > g_{K_I}^*$. If it is further assumed that $\epsilon_S = \epsilon_I$ and $g_{p_S^Z} = g_{p_I^Z}$ (also in accordance with the numerical exercise), then $g_{Z_S}^* > g_{Z_I}^*$. The solution also requires that emissions grow faster than value added. This is true in both sectors if $a_S = a_I > g_{p^Z}$. Thus, asymptotically, the service sector converges to the aggregate economy and emissions grow faster than value added if the price of carbon grows more slowly than TFP. For total emissions to be constant or decreasing in the long-run, $g_{Z_i}^* \leq 0 \leq g_{VA_i}^*$ and the case described does not hold. I discuss other cases in section 2.5.5.

To perform the numerical exercise, the TFP growth rate can be solved for in terms of the

[13] I consider only when $\epsilon_i < 1$ because that is the case in the numerical exercises. However, for $\epsilon_i > 1$ the two cases are simply reversed.

long-run growth rate of the aggregate economy and the population growth rate:

$$a_S = (1 - \alpha_S)(g^* - n) \tag{2.17}$$

2.4 Model Validation : Matching U.S. from 1951-1980

To validate the the model, I calibrate it to the U.S. economy in 1951 and simulate the economy going forward. I then compare model output of the service sector share and fossil fuel intensity with actual values. I find that the model matches the growth rate of the service sector share from 1951 until the early 1980s, but misses the unprecedented rapid growth in services during the 1980s. The model also captures the fall in fossil fuel intensity fairly well up until the early 1970s but misses the transition to a new regime of rapidly falling energy intensity in the wake of the energy price shocks.

2.4.1 Calibration to U.S. economy

Output, fixed assets, full-time equivalent employees and service sector share in 1951 are from the Bureau of Economic Analysis (n.d.). The government sector is excluded from all calculations. Fossil fuel consumption in 1951 and a composite fossil fuel price time series are from the Energy Information Administration (n.d.). Since the model is not designed to capture business cycle fluctuations, I match the 5-year moving averages in 1951 for the service sector share and fossil fuel intensity.[14]

Data on fossil fuel consumption is disaggregated into ‘residential’, ‘commercial’, ‘industrial’ and ‘transportation’. To map their data into the model, I assign ‘industrial’ to industry and ‘residential’ and ‘commercial’ to services. Transportation is split 40.11% into industry and the rest into services. This division is based on the share of transportation purchased by industrial and service sectors in the 1947 U.S. input-output table.

The labour share parameters, $1 - \alpha_i$, are set equal to employee compensation divided by value added for both industry and services.[15] The industrial sector includes mining, manufacturing, agriculture and construction. Transportation is divided as described above for fossil fuels and utilities and petroleum processing are divided in the same manner. The service sector is composed of the remaining sectors.[16] The capital share is one minus the labour share. Since

[14] I will compare the model simulation results with 5-year moving averages of the service sector share and fossil fuel intensity.

[15] Note that excluding the government sector results in a noticeably more capital-intensive economy.

[16] Industry shares: transportation 40.11%, utilities 26.27%, petroleum processing 41.33%. The remainder is allocated to services.

	Industry	Services	Match
Initial output share	0.49	0.51	Data
Capital share (α_i)	0.38	0.51	Data
Labour share (β_i)	0.62	0.49	Data
Energy share (γ_i')	0.0324	0.0322	Data, calculation
Elasticity, F and VA (ϵ_i)	(0.10, 0.547)		See text
Elasticity, Y_I and Y_S (ϵ)	3.0		Service share transition

Table 2.2: Key parameter values. Note that the government sector is omitted.

data for employee compensation by sector only goes back to 1987, I must use the shares from that year in my calibration. The energy share parameters, γ_i, are set equal to the value of fossil fuels used in production divided by value added plus the value of fossil fuel inputs, for each sector.[17]

The elasticity of substitution between industrial goods and services is chosen such that the service sector share follows a similar path to the actual timeseries (5-year moving average). This value is $\epsilon = 3$. Several values of the elasticity of substitution between value added and fossil fuels were tried. Here, I consider $\epsilon_i = 0.54$, which is the value estimated by van der Werf (2008),[18] and $\epsilon_i = 0.10$. The elasticities are the same in both sectors.

The long-run growth rate, $g = 3.3\%$, and the employment growth rate, $n = 1.8\%$, are taken from Acemoglu and Guerrieri (2008). Standard values are chosen for the discount rate, intertemporal elasticity of substitution and depreciation: $\rho = 2\%, \theta = 4, \delta = 5\%$. The rate of TFP growth is given by equation (2.17) and is set equal in both sectors.

2.4.2 Simulation of U.S. economy

The calibrated model is simulated over a 150-year period, although I only focus on the behaviour up to 2011. The differential equations are discretized using the Euler method and a shooting algorithm is used to solve for the time path of the model.[19] Figure 2.2 shows the actual service sector share (5-year moving average) and the simulated service sector share. The model does a good job a matching the path of the service sector share up until 1980. At that point, there is a dramatic increase in the growth of services that lasts for about a decade. Herrendorf et al. (2013) point out that this time period coincides with the decline in U.S. manufacturing which seems to occur in all countries when GDP per capita reaches about 8,000

[17] $\gamma_i = \frac{VF_i}{VA_i+VF_i}$, where VF is the value of fossil fuels used as inputs.

[18] This was estimated for the elasticity of substitution between energy and value added in the U.S., which includes more than fossil fuels.

[19] See Appendix B for details on the shooting algorithm.

(1990 international $). The model cannot capture this regime change in the U.S. economy.

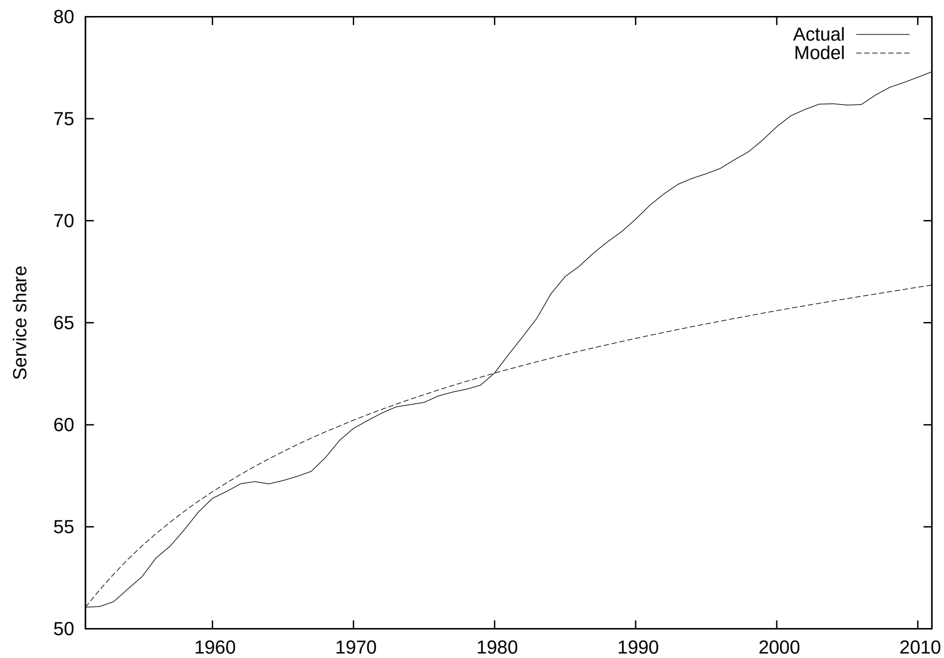

Figure 2.2: The U.S. service sector share is well simulated by the model until about 1980.

Figure 2.3 shows the actual fossil fuel intensity of the U.S. over time as well as the simulated time path for two different values of the elasticity of substitution between fossil fuels and value added. For the higher value, the intensity decreases too slowly from the very beginning of the simulation. The model is simulated using a smaller elasticity parameter of $\epsilon_i = 0.10$ and generates a more rapidly decreasing intensity more consistent with the observed timeseries. This occurs because there is substitution toward fossil fuels away from value added over time, but a smaller elasticity slows that substitution. The substitution is a result of wages increasing sufficiently rapidly such that the price of value added is increasing faster than the price of fossil fuels over most of the simulation. Recall from section 2.3 that for there to be substitution away from fossil fuels TFP must grow faster than the price of fossil fuels, which is not the case here. If there was a greater difference in energy intensity across sectors (0.0324 compared to 0.0322), such a low elasticity would not be required.[20] Since the elasticity plays such an important role in accurately replicating the intensity trajectory, I consider multiple values when simulating the Chinese economy in the next section.

[20]For the case of the Chinese economy I find a larger difference.

There is a clear transition in the rate of decrease of fossil fuel intensity in the early 1970s. This period coincides with the oil price shocks resulting from the OPEC oil embargo. Although the price shocks are present in the simulation, the model cannot generate a strong response as seen in the actual data. This is likely due to transformational changes in the economy that alter the parameter values of the model. I conclude that for the appropriate elasticity parameters, the model presented in the paper correctly simulates both structural change and fossil fuel (or carbon) intensity as long as there are no significant events or changes that dramatically alter the economic environment.

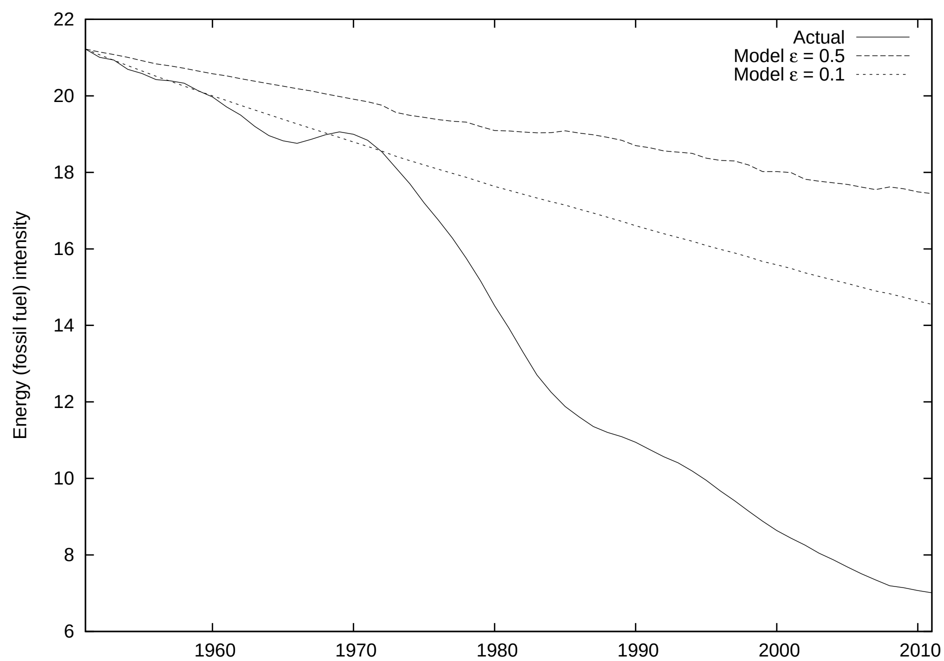

Figure 2.3: The U.S. fossil fuel intensity is well simulated by the model until early 1970s for an appropriate choice of the elasticity parameter.

2.5 Experiments

To quantify the impact of structural change on carbon intensity in a developing economy, numerical experiments compare the relative importance of structural change and efficiency gains in lowering carbon intensity. Output losses from a carbon tax are also calculated to determine the savings to GDP due to structural change. Simulations with different carbon tax time-paths are then compared to study the impact of a dynamically changing tax rate.

The model is calibrated to the Chinese economy. China is chosen because it is the world's leading emitter of GHGs and has a relatively small service sector. Two scenarios are considered for the pace of structural change - slow and fast. The 'slow' scenario assumes China's service sector will evolve in a manner similar to what the U.S. experienced. I also consider a faster scenario because China's economy has been growing much faster than the U.S. did during this phase of development. Due to uncertainty in the fossil fuel-value added elasticity parameters, three values are considered in both scenarios. For consistency with the empirical literature, the Laspeyres additive index is used to quantify the contribution of structural change to lowering carbon intensity.

To carry out counter-factual simulations of the Chinese economy without structural change I simulate a 1-sector economy.[21] These simulations expose the general equilibrium effects of structural change on carbon intensity as prices and demands can adjust dynamically according to the household and firm problems. That is, the Laspeyres index decomposes the intensity along a specific time path in the two-sector model but does not account for the entirely different time path that would occur as a result of a different aggregate production structure in a one-sector economy. For the 1-sector model, I calibrate the model to two identical sectors whose parameters each match those of the aggregate economy. This renders the aggregate production structure fixed in the one-sector economy, apart from TFP growth.

Next, a carbon tax is introduced such that a carbon intensity target is reached in each scenario. That is, the intensity is lowered through an appropriate choice of a carbon tax. This exercise demonstrates how a model without structural change can lead to choosing a tax rate that is too high and overestimating the losses from climate policy.

Finally, I consider different carbon tax timepaths. Many studies of climate change economics find that it is optimal to set the initial carbon price at a low level and then ramp it up with time. The "ramp up" timepath is superior in many models because avoiding emissions is less costly as an economy becomes more developed and the capital stock can be built up over time to accommodate a less carbon-intensive economy. In the first set of experiments a constant carbon tax is introduced and thus most of the response to the tax occurs in the first

[21] A multi-sector model without structural change can be aggregated to a 1-sector model.

period of the tax. Since the model is dynamic, I consider a second set of experiments where tax rates rise at 2% and 5% per year but meet the same emissions intensity reduction targets.

2.5.1 Data and calibration

I calibrate the model to the Chinese economy using economic and energy data from the Chinese Statistical Yearbook (CSY, National Bureau of Statistics of China, 2007), emissions data from the World Development Indicators (World Bank, n.d.) and emission factors from the Energy Information Administration (EIA). Sectoral-level data is from the most recent (2007) input-output table in the CSY (135 industries).

The industry sector includes manufacturing, chemical processing, construction, agriculture and mining (sectors 1-95, with an exception explained below). The service sector includes transportation, retail, financial intermediation, entertainment, healthcare and education (96-135). Power and heat generation and fuel processing are treated uniquely because they are both responsible for significant carbon emissions and serve both the industrial and service sectors. Since 70% of power generation is used by industry, this share is attributed to industry and 30% to services. Similarly, 45% of processed fuels spending is done by industry, thus that sector is divided 45-55. With this division of activities, the emissions from each sector should be accurately modelled as both sectors grow.

The initial shares in output of industry and services are calculated by summing the value added of the respective sub-sectors. The share parameters for labour are calculated by summing "employee compensation" across appropriate sub-sectors and dividing by the corresponding value added. The capital share is 1 minus the labour share. Since I assume that emissions are linear in fossil fuels, $Z_i = \frac{1}{\phi_i} F_i$, the share of emissions is the same as that of fossil fuels:

$$\frac{\partial Y_i}{\partial Z_i} = \frac{\partial Y_i}{\partial F_i}\frac{\partial F_i}{\partial Z_i} \;\Rightarrow\; p_i^Z = \phi_i p_i^F \;\Rightarrow\; \frac{p_i^F F_i}{p_i Y_i} = \frac{p_i^Z Z_i}{p_i Y_i}$$

Thus the share parameter for emissions in each sector, γ_i', is simply the spending on coal, oil and gas relative to value added. To calculate the ratio of emissions in each sector which is used to get the initial price of emissions, the emission factor ϕ_i is needed. This is calculated by taking the energy consumption by fuel type by industry from the CSY and multiplying it by the emission factor for each fuel type from the EIA. The elasticity of substitution between industry and services is chosen such that in the 'slow' scenario structural change roughly matches the historical pace of the United States between 1951 to 1981 (service sector growth from 51% to 63%). In the this scenario, China's service sector grows from 48% to 51% in 5 years, then grows to 63% over the following 30 years. The value for ϵ in this scenario is 3.5. In the 'fast'

	Industry	Services	Match
Initial output share	0.52	0.48	Data
Capital share (α_i)	0.53	0.64	Data
Labour share (β_i)	0.47	0.36	Data
Emissions share (γ_i')	0.10	0.08	Data, calculation
Emission factor (ϕ_i)	3.86	2.14	Data, calculation
Elasticity, Z and VA (ϵ_i)	(0.25, 0.5, 0.76)		See text
Elasticity, Y_I and Y_S (ϵ)	(3.5, 6)		Service share transition
Population growth (n)	0.003		Vennemo et al. (2009)
Capital output ratio ($\frac{K}{Y}$)	1.67		Bai et al. (2006)

Table 2.3: Key parameter values.

scenario $\epsilon = 6$ and the service sectors grows to 72% in 30 years.

van der Werf (2008) estimated values for the elasticity of substitution between energy and value added. A wide range of estimates were found across countries, from 0.1725 for Canada to 0.6053 for Belgium (the U.S. was 0.5470). Su et al. (2012) estimated the elasticity for China and obtained a value of 0.7611 for the time period 1979-2006. However for earlier time periods they obtain a value of 0.26. Due to the variability in these estimates, I consider three values for ϵ_i: 0.25, 0.5 and 0.76. I use the same value for both industry and services. I refer to the case where $\epsilon = 3.5$ and $\epsilon_i = 0.76$ as the baseline scenario.

A population growth rate of 0.3% is taken from Vennemo et al. (2009), and the initial capital output ratio of 1.67 is taken from Bai et al. (2006).

A long-run growth rate of 6% is chosen. China's growth has been above 10% for much of the past decade, falling below 8% more recently. Since no fast-developing country has been able to maintain growth near 10%, I argue that 6% is a reasonable compromise between a growth rate faster than developed countries but slower than recent growth in China.[22] Standard values are chosen for the discount rate, intertemporal elasticity of substitution and depreciation: $\rho = 2\%, \theta = 4, \delta = 5\%$. The initial aggregate output and emissions are taken from the World Bank (n.d.).

For the calibration of the one sector model, I re-calculate aggregate labour, capital and emission shares. This is done in the same fashion as described above except there is no division of industries. The values are: $\alpha = 0.59, \beta = 0.41, \gamma' = 0.094$. I then run the two-sector model with those parameter values in each sector and the initial output, labour and emissions divided evenly between the two sectors.

[22]6% is the long-run growth rate, but convergence is from above. Initial growth is around 7%.

2.5.2 Numerical simulations

The goal of the simulations is to determine:

1. How much structural change contributes to lowering carbon intensity;
2. The cost savings as a result of structural change for meeting emissions reduction targets;
3. The optimal time-path for a carbon tax.

First, I use the Laspeyres additive index to quantify the respective roles of efficiency gains and structural change in reducing carbon intensity. To determine the importance of general equilibrium effects, I then compare the two structural change scenarios to a scenario without structural change. I also compare output losses from a carbon tax calibrated so that specific intensity reduction targets are achieved across scenarios. I consider two rates of structural change throughout to see how the speed of the transition affects the results. I show that for sufficiently large elasticities of substitution between value added and emissions, structural change is quantitatively important.

I also examine the importance of different dynamic carbon price series. I compare a constant carbon tax to taxes that increase at 2% and 5% per year where they all achieve the same emissions intensity reduction. I find that non-constant taxes that begin at low rates and ramp up can achieve the same emissions reduction targets at lower cost.

Overview of model output

The model generates significant structural change from industry to services. This occurs because services are more capital intensive than industry and the capital-labour ratio increases with time. Figure 2.4 shows the service sector share of output increasing from 48% to roughly 61% after 30 years for the baseline scenario.

Figure 2.5 shows the sectoral and aggregate carbon intensities decreasing for the baseline scenario. After 30 years, the aggregate intensity has decreased by 27%. In "year 0" (the year in which the model is calibrated to data) the aggregate carbon intensity is 1.9, nearer to the intensity of the industrial sector, 3.1, than to the service sector intensity, 0.7. However the aggregate intensity converges to the intensity of the service sector over time. After 100 years, the aggregate intensity is nearer to that of the service sector, which makes up over 80% of the economy at that point.

The aggregate intensity is given by $I = \lambda_I I_I + \lambda_S I_S$, where λ_i gives the share, or weight, of each sector and I_i are the sectoral intensities. The intensity changes over time due to changes in the shares and the sectoral intensities. The Laspeyres additive index is a method of determining the contribution of efficiency gains and structural change (the weighting) to reducing

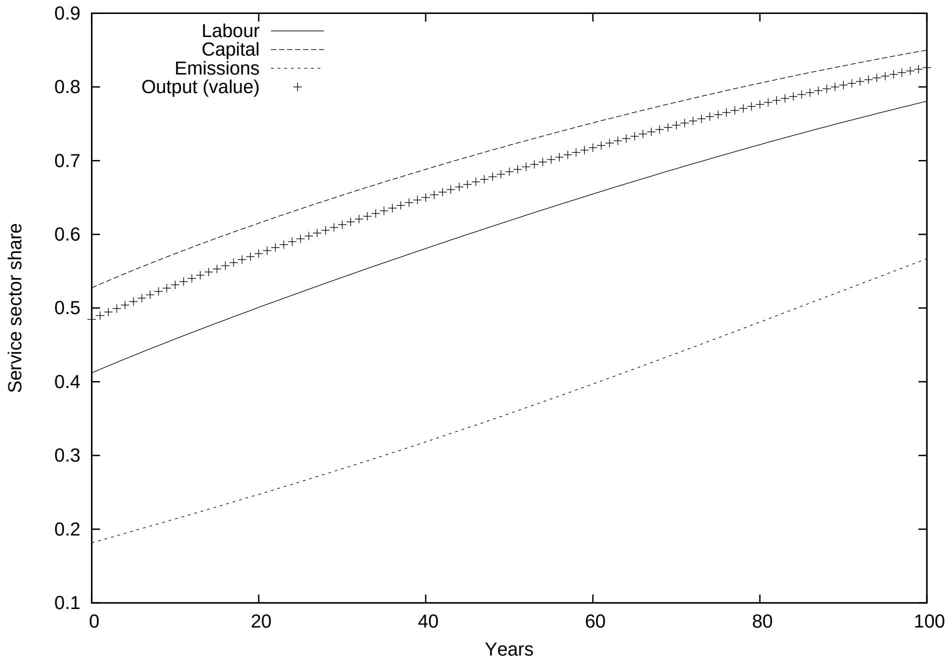

Figure 2.4: Structural change: The service sector shares of output, capital, labour and emissions increase over time (baseline scenario).

intensity. This structural change component is computed by using the *initial* sectoral intensities and *current* sectoral shares to calculate the reduction in intensity had there not been efficiency gains. The efficiency contribution is calculated in the opposite way, and there is a small residual term.[23] Using the index, structural change is responsible for a 15.1% intensity improvement over the first 30 years in the baseline scenario. This compares to a 14.7% improvement as a result of efficiency gains. Thus, the economy is moving toward the less carbon-intensive service sector and this is significantly lowering the carbon intensity.

The decrease in carbon intensity not due to structural change comes via sectoral intensity gains. Sectoral carbon intensities are given by $I_i = \frac{Z_i}{p_i Y_i}$. Figure 2.6 shows the different growth rates in the service sector for the baseline scenario (the story is the same in the industrial sector). As there is little movement in the price of services, the decreasing intensity is a result of output (quantity) growing faster than emissions at the sectoral level. Emissions are growing faster than value added, meaning firms are substituting toward emissions (fossil fuels). This occurs because the price of emissions remains constant while wages are increasing, driving substitu-

[23] See Ang and Zhang (2000) for details of different index methods.

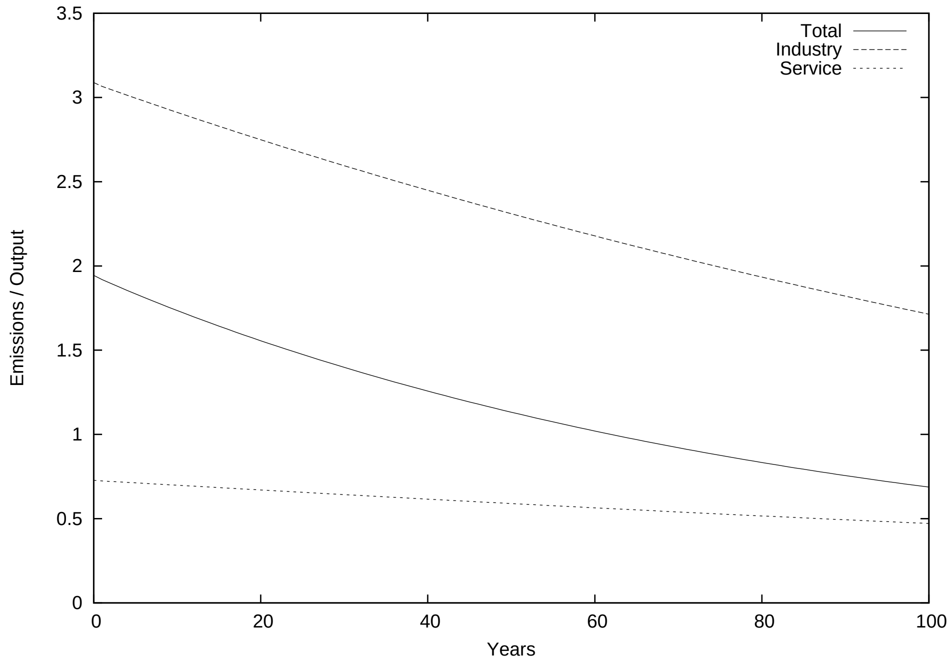

Figure 2.5: Carbon intensity by sector (baseline scenario).

tion away from value added. However, the sectoral emissions intensity decreases nonetheless because TFP growth offsets the growth in emissions. That is, firms become more efficient in the use of all inputs and their ability to produce more with fewer inputs compensates for the relative increase in the use of emissions compared to value added.

Table 2.4 shows the rate of structural change has almost no impact on the efficiency contribution to reducing emissions intensity (of course it does affect the structural change component). Meanwhile, the elasticity parameter for emissions and value added has almost no effect on structural change and primarily affects efficiency.[24] This occurs because the relative prices of emissions and value added are impacted by a lower elasticity roughly equivalently in both sectors. One interesting feature of the model is that the service share actually increases slightly as ϵ_i goes from 0.76 to 0.5, but then decreases as ϵ_i is furthered lowered to 0.25. This occurs because there are two competing effects of lowering the elasticity. Over time, the price of value added increases through wages while the price of emissions remains constant. However, since a lower elasticity makes it more difficult to substitute toward emissions this favours services relative to a higher elasticity scenario. The other effect comes through the initial calibration; as

[24]The residuals are very large for small ϵ_i, rendering those results less informative.

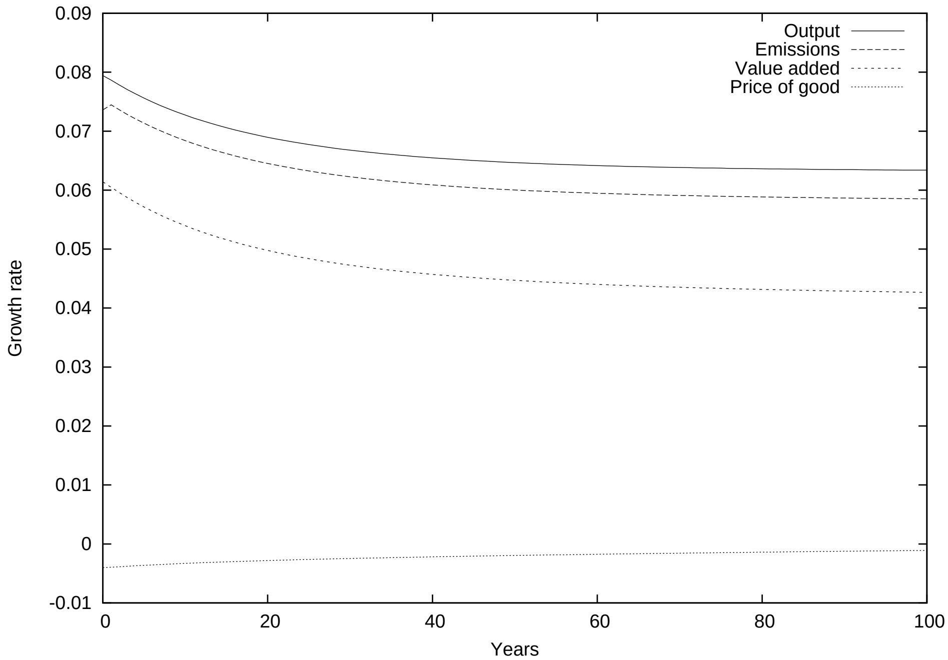

Figure 2.6: Service sector growth rates.

the elasticity is lowered, the initial price of emissions relative to value added decreases. This favours the more emissions intensive industrial good. These two competing effects result in the service share not being monotonic in ϵ_i over the initial 30 year period.

Comparison with 1-sector model

The Laspeyres index is a backward-looking method for quantifying the relative impacts of structural change and efficiency gains in reducing carbon emissions intensity. This approach makes sense for backward looking empirical studies, especially where there are many sectors. An alternative approach to quantifying structural change impacts is to compare with a one-sector model. Structural change allows the sectoral intensities to evolve differently due to changes in relative prices and the Laspeyres index cannot account for different time paths. Understanding how structural change impacts *models* is key for cost-benefit analyses used to inform policy-making. Furthermore, index methods have residuals in addition to the structural and intensity components. These residuals cannot be attributed to either mechanism; comparing to a 1-sector model avoids this issue.

This exercise shows the index method slightly overestimates the impact of structural change;

Scenario	Service share	Intensity change	Structural component	Efficiency component	Residual
ϵ = 3.5 ('Slow')					
ϵ_i = 0.76	**60.9%**	**-27.3%**	**-15.1%**	**-14.7%**	**+2.5%**
ϵ_i = 0.50	61.5%	-39.0%	-15.8%	-28.3%	+5.1%
ϵ_i = 0.25	61.2%	-47.8%	-15.5%	-39.1%	+6.8%
ϵ = 6.0 ('Fast')					
ϵ_i = 0.76	71.8%	-38.5%	-28.4%	-14.9%	+4.8%
ϵ_i = 0.50	72.8%	-48.7%	-29.5%	-28.7%	+9.6%
ϵ_i = 0.25	72.4%	-55.7%	-29.0%	-39.6%	+12.9%

Table 2.4: Contribution of structural change to reducing carbon intensity after 30 years for different elasticity parameters using Laspeyres additive index. Baseline scenario is bolded.

however structural change remains quantitatively important. Furthermore, as the elasticity of substitution between emissions and value added decreases, the contribution of structural change decreases. This was less clear with the index method.

Figure 2.7 shows emissions intensity across the three structural change scenarios. There is a divergence in intensity with time whereby more structural change delivers greater intensity reductions. This is a result of the less emissions intensive service sector growing to take up a larger portion of the economy.

The first column of table 2.5 shows that carbon intensity only drops by 15.1% after 30 years in the 1-sector model compared to 27.3% in the model with slow structural change (for ϵ_i = 0.76). Thus structural change allows for a 12.1% decrease in emissions intensity (index method yielded a 15.1% contribution). In the 'fast' scenario intensity drops by 38.5%, thus 'fast' structural change lowers emissions intensity by an additional 23.4%; more than the efficiency gain over that time period. For ϵ_i = 0.50, 'slow' structural change adds 39.0%−28.8% = 10.2% to the reduction in emissions intensity. As ϵ_i is further lowered to 0.25, 'slow' structural change add 47.7% − 39.9% = 7.8% to the reduction in emissions intensity. Thus 'slow' structural change adds 12.1%, 10.2% and 7.8% to the reduction in emissions intensity for ϵ_i = 0.76, ϵ_i = 0.50 and ϵ_i = 0.25, respectively (the story is the same for the 'fast' scenario). In addition, the efficiency contribution from the 1-sector model increases as ϵ_i decreases. Thus, as the elasticity of substitution between emissions and value added is lowered, the importance of structural change to reducing intensity is reduced. This is not surprising since lowering the elasticity parameter had little impact on the size of the service share after 30 years as seen in table 2.4. This occurs because for a low elasticity, the growth of emissions is significantly slowed in each sector. As a result, the relative benefit of the less emissions-intensive service sector is diminished.

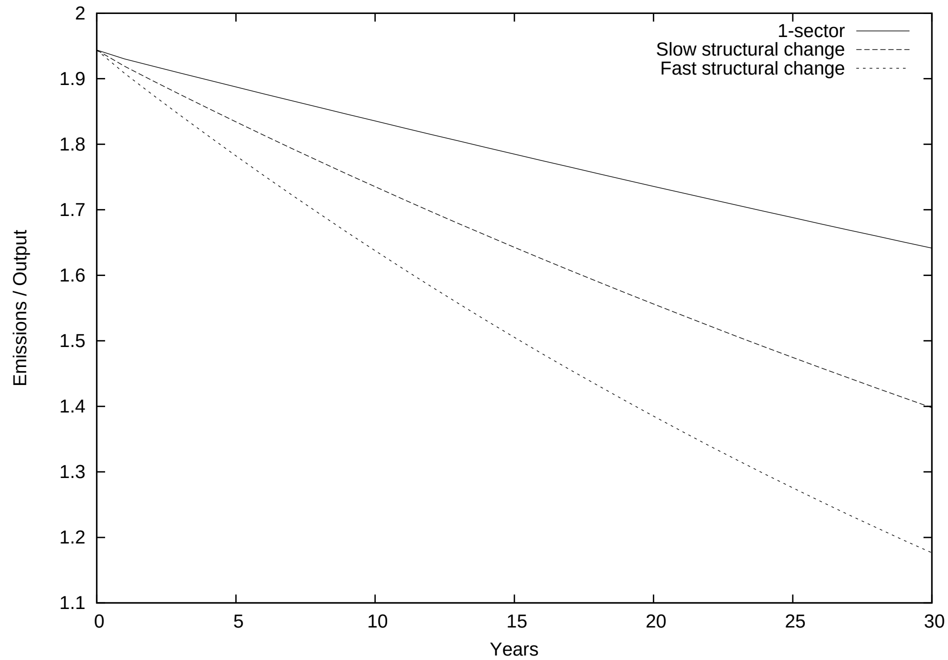

Figure 2.7: Carbon intensity - 1-sector model vs 2-sector model (ϵ_i = 0.76).

Output loss from climate policy

To study the economic impacts of climate policy, I compare two policy goals: a 35% and 65% reduction in emissions intensity after 30 years. The 35% goal roughly corresponds to the U.S.'s fossil fuel intensity reduction from 1951 to 1981. The 65% goal is an extension of China's Copenhagen commitment of reducing carbon intensity by 40%-45% by 2020 over 2005 levels. A 40% reduction over 15 years is roughly equivalent to a 3.5% decrease per year. Over 30 years that rate of decrease works out 65%. Comparing the different scenarios for a fixed target is appropriate since government policy typically targets emissions or emissions intensity, and this will show the importance of structural change for a fixed target.

To meet the emissions intensity reduction target, I calibrate the required carbon tax. This tax raises the price of emissions, thus there is substitution toward value added (or less substitution toward emissions) in both sectors. This raises each sector's prices, however industry's price is impacted more significantly because it is more emissions intensive. In the world with more structural change, a lower tax is required because there is a greater reduction in intensity even without the tax. Thus the loss in output decreases as structural change increases.

Table 2.5 shows the carbon tax needed to reduce emissions intensity by 35% and 65%

across scenarios, as well as the corresponding loss in output from such a tax. For the 35% reduction policy, a tax is not needed if $\epsilon_i = 0.25$, nor in the 'fast' scenario because the intensity is reduced substantially enough without the tax. However, for $\epsilon_i = 0.76$, a $2.50/t tax is needed in the slow scenario resulting in a 0.7% GDP loss. This is significantly smaller than the $9/t tax needed in the 1-sector model resulting in a 2.7% GDP loss. For the 65% reduction target, a tax is needed in all scenarios and for all elasticity parameters, however the tax and corresponding output losses are tiny for $\epsilon_i = 0.25$. Structural change results in GDP savings for all elasticity values, however the savings are very large for $\epsilon_i = 0.76$ as the loss is 9.1% in the 1-sector model compared to 5.3% and 4.1% in the 'slow' and 'fast' scenarios, respectively. This is because structural change is generating larger emissions reduction even without the tax, but in addition the tax drives even greater structural change in the simulations where that is possible. In the baseline scenario the service sector is 60.9% of the economy after 30 years with no tax, 61.2% in the 35% reduction case and 62.1% in the 65% reduction case.

At $\epsilon_i = 0.25$ losses are virtually non-existent across all scenarios, however greater structural changes still generates slightly smaller losses. The lower values of ϵ_i result in larger intensity reductions (even in the absence of a tax) because as the wage increases is it more difficult to substitute toward relatively cheaper emissions compared to when ϵ_i is higher. Since it is relatively more difficult at lower elasticities to substitute toward emissions as they become cheaper, it is correspondingly less costly to reduce emissions when the price of emissions goes up via the tax. While structural change is much less important for these small elasticities, it is important to note that reducing emissions becomes virtually costless at these parameter values.

Note that China's Copenhagen commitment is to reduce carbon intensity by 40-45% over 2005 levels by 2020. Taking 2007 to be the initial year in the simulation, if $\epsilon_i = 0.76$, meeting the target would require a $5/t tax without structural change, a $1/t tax for 'slow' structural change and no tax for 'fast' structural change. For $\epsilon_i = 0.25$ the tax is not needed in any scenario. With recent emissions data it is possible to compare the first few years of model output to actual data. The model simulations begin in 2007 and predict 7,998 kt of emissions in 2010. Actual emissions in 2010 were 8,287 kt. Therefore since China is slightly behind the model prediction, a slightly higher tax may be required.

Increasing carbon prices

There is debate in the literature over how aggressively a carbon tax should be implemented (for a review see Tol, 2009). Many argue that a tax should be implemented gradually, ramping up over time. This is because is will be less costly to mitigate emissions later when economies are more developed and technology has improved. Furthermore, it will give more time to replace aging equipment with more efficient machines and to the see the results of R&D. However,

Scenario	No tax Intensity Δ	35% reduction Tax level	35% reduction Output Δ	65% reduction Tax level	65% reduction Output Δ
1-sector					
$\epsilon_i = 0.76$	-15.1%	$9/t	-2.7%	$45/t	-9.1%
$\epsilon_i = 0.50$	-28.8%	$0.65/t	-0.2%	$10/t	-1.7%
$\epsilon_i = 0.25$	-39.9%	N/A	0%	$0.08/t	-0.01%
$\epsilon = 3.5$ ('Slow')					
$\epsilon_i = 0.76$	**-27.3%**	**$2.50/t**	**-0.7%**	**$28/t**	**-5.3%**
$\epsilon_i = 0.50$	-39.0%	N/A	0%	$4/t	-0.6%
$\epsilon_i = 0.25$	-47.8%	N/A	0%	$0.007/t	-7E-4%
$\epsilon = 6.0$ ('Fast')					
$\epsilon_i = 0.76$	-38.5%	N/A	0%	$23/t	-4.1%
$\epsilon_i = 0.50$	-48.7%	N/A	0%	$3/t	-0.4%
$\epsilon_i = 0.25$	-55.7%	N/A	0%	$0.003/t	-2E-4%

Table 2.5: The first column is the intensity reduction after 30 years with no tax. Columns 2-5 show the tax level required to reduce emissions intensity by 35% and 65% over 30 years and corresponding output loss.

others argue that urgent action must be taken because emissions remain in the atmosphere for 100 years and if urgent action is not taken now it may be too late. This model does not have damages so there is little incentive to take urgent action. However, consider that as the service sector grows the rate of change must slow since the share is bounded at 100%. It may be that since structural change is a one-time event, an aggressive carbon tax is optimal since it speeds up the structural change process, hence lowering emissions at low cost. That notion will be tested here.

I next consider carbon taxes that are increasing in time. This could be as a result of policy or a proxy for increasing fossil fuel prices.[25] The constant tax could be seen as the most "aggressive" implementation since it starts out higher. I compare carbon tax timepaths that all achieve the same target of reducing emissions intensity by 65% over 30 years, as in the previous section. The increasing timepaths do so at 2% and 5% per year, and they are compared to the constant tax.[26] The initial level of the carbon tax is chosen such that the emissions intensity is reduced by 65% over 30 years.

Table 2.6 shows the initial tax level and output loss across tax timepaths and scenarios. The tax rate beginning at the low level and increasing at 5% per year outperforms the 2% tax in terms of output loss across all scenarios. The 2% per year tax outperforms the constant tax.

[25]Note that real energy prices have been roughly constant over long stretches of time in the past century.

[26]The 2% rate is chosen because it is equal to the discount rate, and 5% is just below the rate of GDP growth in the simulations.

	Constant tax		2% increase		5% increase	
Scenario	Initial tax	Δ Output	Initial tax	Δ Output	Initial tax	Δ Output
1-sector						
$\epsilon_i = 0.76$	\$45/t	-9.1%	\$25/t	-7.7%	\$11/t	-6.3%
$\epsilon_i = 0.50$	\$10/t	-1.7%	\$5/t	-1.3%	\$2.50/t	-1.2%
$\epsilon_i = 0.25$	\$0.08 /t	-0.01%	\$0.04/t	-8E-3%	\$0.02/t	-7.7E-3%
$\epsilon = 3.5$ ('Slow')						
$\epsilon_i = 0.76$	**\$28/t**	**-5.3%**	**\$17/t**	**-4.7%**	**\$7/t**	**-3.5%**
$\epsilon_i = 0.50$	\$4/t	-0.6%	\$2.50/t	-0.5%	\$1/t	-0.4%
$\epsilon_i = 0.25$	\$0.007/t	-6.8E-4%	\$0.0035/t	-4.7E-4%	\$0.0015/t	-3.5E-4%
$\epsilon = 6.0$ ('Fast')						
$\epsilon_i = 0.76$	\$23/t	-4.1%	\$13/t	-3.3%	\$5.50/t	-2.4%
$\epsilon_i = 0.50$	\$3/t	-0.4%	\$1.50/t	-0.3%	\$0.70/t	-0.2%
$\epsilon_i = 0.25$	\$0.003/t	-1.5E-4%	\$0.0015/t	-5.9E-5%	\$0.0007/t	-1.8E-5%

Table 2.6: Initial tax required to reduce emissions intensity by 65% over 30 years for different carbon tax time paths. Output losses are at year 30.

For example, in the baseline scenario a 65% intensity reduction after 30 years can be achieved by a \$7/t tax increasing at 5% per year for 3.5% loss of GDP. A constant tax of \$28/t would be needed to achieve the same reduction and would cost 5.3% of GDP. Thus the model indicates that for a given carbon intensity target, it is optimal to set the tax at a low level initially and increase it over time.

Note the model considered here does not account for several factors, most notably damage to output from climate change. Therefore, this paper only argues that the structural change mechanism does not help the case of the "initially high" carbon tax. It remains possible that this tax is optimal if the damage from climate change was sufficiently severe without immediate, strong mitigation of emissions. This also does not account for government commitment issues.

2.5.3 Sensitivity to parameter changes

Although the sensitivity of the model to the elasticity parameters has been detailed throughout section 2.5.2, there are a few other parameters whose robustness is worth considering. In this section I test the sensitivity of the model to the long-run growth rate, the capital share parameters, the emissions/fossil fuel share parameters and the discount rate.

In my simulations I chose a long-run growth rate of 6% for reasons described in section 2.5.1, however China has experienced growth over 10% in the past decade. The long-run growth rate parameter impacts the TFP growth rate directly (as seen in equation 2.17), and the pace of structural change indirectly. For a long-run growth rate of 10% the service sector share at 30 years goes from 61% to 63% and the intensity reduction goes from 27.3% to 38.9%. About 2% of the change can be attributed to structural change while the rest is efficiency improvements. For a long-run growth rate of 3%, closer to developed country growth, the service sector share drops to 60% at 30 years and the intensity improvement is only 24.8% with structural change taking on slightly more importance. Therefore, the quantitative change for lower growth rates is small, while for sustained high growth efficiency gains have greater importance but the role for structural change remains.

Another potentially important set of parameters are the capital share values. The calculated economy-wide capital shares for China were 0.53 and 0.64 for industry and services, respectively. The values calculated for the U.S. simulations were 0.38 and 0.51 (without government). It may be that as China's economy develops, the capital share will converge toward that of developed economies. If the Chinese baseline scenario is simulated with the U.S. capital share values, structural change proceeds at nearly the same pace. However, the intensity drop over 30 years goes from 27.3% to 34.1% as a result of sectoral efficiency gains. This occurs because the reduction in the capital share parameters makes value added much cheaper relative to emissions. Thus if China becomes less capital intensive, efficiency may become more important in terms of reducing emissions intensity.[27] However, the impact of structural change remains quantitatively important. Furthermore, it may take many years for China's economy to become less capital intensive, at which point the benefits of structural change will have already been largely captured.

In addition to the capital/labour share parameters, there are also the fossil fuel share parameters to consider. The values calculated from the CSY for the Chinese simulations were 0.10 and 0.08 for industry and services, respectively. It is possible that production in China will becomes less energy intensive as the economy develops beyond what is captured in the model. Decreasing the share parameters to 0.05 and 0.04 has virtually no impact on the rate of structural change. However, the intensity improvement goes from 27.3% to 34.4%. Once again the sectoral efficiency improvements occur because the price of emissions relative to fossil fuels goes up when the model is calibrated with lower emission share values.

The discount rate is at the heart of debates over the economic cost of climate change. As there are no damages in this model, the debate around the discount rate does not apply. Nonetheless I will briefly discuss how it impacts the results in this model. If the discount rate were lowered from 2% to 0.1%, the pace of structural change would increase because investment would become more attractive and capital favours the service sector. At 30 years,

[27] However if the capital share converges to that of developed countries then the growth rate might also be expected to converge. As discussed above, a lower growth rate would result in smaller efficiency gains to at least partially offset the effect of the decreased capital share.

the service sector share would go from 61% in the baseline scenario to 66% for $\rho = 0.001$ with intensity improving accordingly. However, recall the elasticity parameter ϵ governing substitution between industry and services was chosen to match a desired pace of structural change. Thus if the discount rate was lowered I could simply choose a lower value for ϵ and the quantitative results would be unchanged. Since my model does not include climate change damage the choice of the discount rate should not be controversial.

2.5.4 Other developing countries

I have focused on China as it is the world's largest emitter of CO_2 emissions and largest developing economy. However, there a several other developing countries with significant emissions including in order: India, Russia, Mexico, South Africa, Indonesia and Brazil.[28] Here, I do rough recalibrations of the model to these countries to see how their emissions intensities may be affected by structural change. I find that countries with smaller service sectors, such as China and Indonesia, can reduce emissions intensity more easily because they have the ability to transition a significant segment of their economy toward services. Meanwhile, countries with relatively large service sectors like South Africa and Brazil may find it very difficult to reduce emissions.

The parameters I change for this analysis are the initial service sector share, the rate of structural change, the long-run growth rate, the population growth rate and the fossil fuel share parameters. The sectoral capital shares are assumed to be the same as for China. The initial service sector share is taken from the World Bank (n.d.), as is the ratio of GDP to unit of energy use ($\frac{Y}{E}$). The fossil fuel share parameters are adjusted for country i by multiplying the values used for China by $(\frac{Y_i}{E_i})/(\frac{Y_{\text{China}}}{E_{\text{China}}})$. The population growth rate is taken to be the average projected growth rate over the next 30 years from the World Bank. The rate of structural change is taken to roughly match the U.S. rate starting from the given initial service sector share (making a downward adjustment for the period of rapid service growth in the 1980s). The long-run growth rate is selected by comparing recent growth rates to China and adjusting accordingly. The elasticity of substitution between value added and emissions used in all simulations is $\epsilon_i = 0.76$. The parameters used are given in table 2.7.

The data shows the size of the service sector varies significantly across countries, as do energy intensities. All of the countries considered here, except Indonesia, have larger service sectors than China, and it is expected that countries with larger service sectors would have less scope for reducing emissions through structural change. In section 2.5.3 it was shown that lower fossil fuel share parameters lead to greater reductions in emissions intensity due to

[28] I omit Iran and Saudi Arabia because they are large oil producers and their emissions are likely to be affected by a variety of factors not considered here.

	Initial service share	$\frac{Y}{E}$	L-R growth rate	Pop. growth rate
China	49%	3.7	6.0%	0.3%
India	57%	5.3	5.0%	0.9%
Russia	59%	2.9	4.0%	-0.3%
Mexico	60%	7.9	2.5%	0.6%
South Africa	69%	3.5	2.5%	0.3%
Indonesia	38%	4.7	3.0%	0.5%
Brazil	68%	7.5	3.0%	0.4%

Table 2.7: Data used to calibrate model across countries.

efficiency, but lower growth rates decrease the role for efficiency. China may have an advantage in both the structural component (due to a small service sector) and efficiency as it has a high growth rate and high energy intensity. Russia may do relatively better than other countries in terms of efficiency, if it can return to a high growth rate, due to its higher energy intensity.

Table 2.8 shows the reduction in emissions intensity across countries as well as the structural contribution using the Laspeyres additive index. The countries with the smallest service sectors, China and Indonesia, make much larger intensity reductions than other countries. Structural change turns out to be even more important for Indonesia as the efficiency gains are minimal; this is due to the lower growth rate.[29] South Africa and Brazil may have a particularly difficult time lowering emissions intensity as their service sectors are already quite large. It must be noted that I have assumed all countries share some parameter values with China. If some of these differ, in particular the elasticity of substitution between emissions and value added, the story could be different. I have shown that a lower elasticity decreases the importance of structural change, as does a lower capital share. Therefore, if anything, developing countries other than China may see even less of a role for structural change in reducing emissions.

2.5.5 Intensity vs. total emissions

Throughout the numerical exercise the quantity of interest has been emissions intensity. I have focused on intensity because China and many developing countries have based their policy on an intensity target and not a level target. However, avoiding potentially dangerous climate change depends on stabilizing emissions, not emissions intensity. It is possible to continue reducing emissions intensity indefinitely without ever lowering actual emissions, and in fact this is the case in the simulations presented above.

[29]Higher growth leads to more efficiency through TFP growth, however total emissions growth may be worse.

Scenario	Service share	Intensity change	Structural component	Efficiency component	Residual
China	49% - 61%	-27.3%	-15.1%	-14.7%	+2.5%
India	57% - 67%	-19.7%	-10.3%	-10.9%	+1.5%
Russia	59% - 68%	-19.0%	-9.1%	-11.2%	+1.4%
Mexico	60% - 69%	-13.7%	-8.7%	-5.9%	+0.1%
South Africa	69% - 74%	-10.0%	-4.3%	-6.2%	+0.1%
Indonesia	38% - 53%	-29.9%	-23.9%	-7.9%	+1.9%
Brazil	68% - 73%	-11.3%	-4.8%	-7.2%	+0.1%

Table 2.8: Service sector growth over 30 years and contribution of structural change to reducing carbon intensity across countries (using Laspeyres index).

Consider the case where emissions are stabilized, that is $g^*_{Z_S} = g^*_{Z_I} = 0$. For a growing workforce or capital stock it must be the case that $\frac{VA_i}{Z_i} \rightarrow \infty$. By equation (2.16), $g^*_i = a_i$. Now, for services to grow more rapidly than industry it is required that $a_S > a_I \Rightarrow g^* = g^*_S = a_S$ (this violates the stylized fact that $a_I > a_S$).[30] Following from equation (2.12), and using the baseline parameter values, the following is obtained:

$$g^*_{P^Z_S} = a_S \tag{2.18}$$

$$g^*_{P^Z_I} \approx 1.6a_S - 0.03a_I \tag{2.19}$$

Therefore the carbon tax rates would have to be different across sectors, with the service sector carbon tax rate growing at the pace of productivity growth and the industrial sector carbon tax growing even faster. However, this has violated a stylized fact that $a_I > a_S$; if I had chosen to violate a condition on one of the elasticity parameters instead then slightly different results would be obtained. The key is that for total emissions to stabilize or decline, the carbon tax would have to be different across sectors, each increasing at rates dependent on parameter values.

2.6 Discussion

With the growing global focus on mitigating climate change and the important role for developing countries, more studies of the economic impacts of climate change and associated policies

[30] I could have chosen $\epsilon_i > 1$ and the solution from section 2.3 would hold, but estimated values of ϵ_i are always below 1. I could have also chosen $\epsilon < 1$, but then quantity and value shares would not move in the same direction, as in the data.

are being conducted. However, the role for structural change in reducing emissions has not been previously studied; in this case, the growing share of the service sector as an economy develops. This can be an important consideration because services are typically much less carbon intensive than industry.

This paper has shown the structural change is quantitatively important to lowering carbon intensity, especially over the next 30 years where the dynamic effects are most important. For China, assuming standard parameter values, I find a 27% reduction in emissions intensity after 30 years compared to only 15% in a one-sector model. As a point of comparison, Wing (2008) found that structural change accounted for roughly 70% of the energy intensity decrease in the U.S. over the 20-year period beginning in 1958 (when the U.S. service sector was just over 50% of the economy).[31] It has been speculated that China's Copenhagen climate target of reducing its emissions intensity by 40-45% by 2020 compared to 2005 would occur under business as usual. However, the model determines that this not the case; a price on carbon will be needed. Meeting the target would require a constant carbon tax of $1/t.[32]

The implication of these results is significant. They show that for a given intensity target, the economic loss is much lower than what would be expected based on an analysis that does not account for structural change, especially for countries with small service sectors. I find that Indonesia, with a 38% service sector share, will cut its emissions intensity by 30% over 30 years under BAU, compared to a 14% decrease for Mexico, which has a 60% service sector share. This opens the door for small service sector countries to set more ambitious climate policy (assuming they follow the typical development path and do not grow their industrial share). It also reinforces the importance of country-specific climate targets. Some climate policy studies using large CGE models attempt to account for structural change via model parameters, for example by changing consumption share parameters at each timestep in the simulation (e.g., see Paltsev et al., 2012). This approach increases the parameter space considerably which adds to the margin of error in the results. The results presented in this study provide a reference point for assessing whether economic simulations are adequately capturing structural change and its response to policy.

In this study, I also find that the optimal time path of the carbon tax is such that the tax begins low and increases with time. A modest initial carbon tax rate would have a modest cost for an industry-based economy, and as the tax increases the negative impact would be limited by the growth of services. The timing issue may also be particularly important for developing countries as there are an abundance of new capital expenditures, especially in energy, to satisfy the rapid economic growth. The increasing tax would incentivize cleaner energy development

[31] This empirical study included 35 sectors, thus there was more scope for structural change to have an impact.
[32] A carbon price is part of China's current 5-year plan but has not yet been implemented.

without excessively punishing the present energy producers. In more developed economies, there may be much more significant adjustment costs of moving to cleaner energy.

The results also matter from a developed country perspective. Presuming it will be more costly for developing countries to reduce emissions (see Chapter 4), it is likely that developed countries will have to make transfers to developing countries to offset economic losses. However, transfers may not have to be as large when structural change is taken into account. Furthermore, it may be more important to focus efforts on countries that already have large service sectors as they will have more difficulty reducing their emissions. This would imply focusing more on India than China. It would also mean concentrating much more on African nations because unlike Western and Asian economies, they tend to skip the growth in industry as they develop and go straight from agriculture and other primary industry to services.[33] South Africa in particular has a very carbon-intensive economy with a small industrial sector.

One area for future work is the role of trade in structural change and carbon emissions. As the developed economy service sectors grew rapidly in the 1980s and 1990s, manufacturing in Asia also grew rapidly at least in part because many manufacturers relocated to less economically developed countries. However, the global share of services has increased from 52% in 1970 to 70% in 2012, showing that the increase in services is not just a story of offshoring manufacturing. Furthermore, China has seen its service sector grow from 20% in 1980 to 50% today even as it has become a base of manufacturing. While much of this can be attributed to a shrinking agricultural sector, the manufacturing share growth has levelled off over the past decade. Based on the experience of developed countries, China's manufacturing sector may be expected to decline in the near future as its GDP per capita approaches the threshold of around $8,000. Therefore, it is expected that service sectors in developing countries will continue to grow. Nonetheless, trade clearly impacts sectoral composition, especially for export-driven countries like China. Furthermore, from a global perspective manufacturing must occur somewhere. For example, if manufacturing moves to countries in Southeast Asia and Africa, where would it go next? Since it does not matter where the emissions originate in terms of climate change, it is important to understand how *global* structural change impacts emissions. However, this is a great challenge because there is still much to be learned about the relationship between structural change and trade, let alone the impact on emissions.

[33]Latin American economies also tend to exhibit this characteristic, however they also tend to be low carbon economies and thus less important to slowing global emissions. Brazil, for example, has the carbon intensity of a developed country.

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Chapter 3

A CGE framework for modelling the economics of flooding and recovery in a major urban area

Climate change is expected to cause more extreme weather (including intense precipitation), sea level rise and melting snow caps (IPCC, 2014). These factors can lead to an increased frequency and severity of flooding. This can further be exacerbated by land subsidence. As a result, cities face decisions about how to deal with the prospect of increased flooding. Possible adaptation measures to this threat include options like diking and sea walls, drainage and managed retreat from vulnerable areas. In order to make informed policy governments require estimates of the economic costs associated with flooding compared to the costs and benefits of various adaptation measures.

There are several aspects to the cost of flooding. The first and most obvious is physical damage to capital, such as homes, buildings, equipment and infrastructure. This can often be determined after the flood through insurance claims and disaster assistance payouts. Predicting flood damages typically uses information based on damages caused by previous floods. For example, engineers have developed damage formulas based on flood depth and the type of building called stage-damage curves. Apart from physical damages, there are also output losses as a result of lost economic activity.[1] For example, if a computer chip manufacturer has its output halved as a result of damaged equipment it will not be able to satisfy all of its orders. Consequently, a cellphone maker who had no damage from the flood may see a drop in output due to a shortage of inputs. Furthermore, incomes will be reduced leading to a decrease

[1] It is important not to naively add output losses to direct damages in order to estimate total losses. Part of the output loss is the loss of returns on damaged capital. Adding direct and output losses to get an estimate of total loss would involve some double-counting. See Davies (2015).

in consumption and savings of households. This can further impact trade and government revenues.[2]

This paper develops a framework for studying the economic impacts of flooding and the subsequent recovery. Consider a flood that strikes a particular geographic area of a city. For the duration of the flood, economic activity in that area will be suppressed.[3] Due to the localized nature of the flood, certain industries are more likely to be affected than other as industries tend to cluster together (Porter, 2000). Goods produced by flood-impacted industries will be in short supply. This shortage will reverberate throughout the entire economy through supply chain linkages. Once the flood recedes, likely after a period of at least several days for a severe flood, damaged capital stock must be replaced or repaired and output in affected industries will remain below pre-flood levels. Investment will increase and flow to sectors with now higher marginal products of capital, notably those with capital damages. Exports will decrease along with production, meanwhile there may be an increase in demand for imports to satisfy the demand that cannot be met locally. Income tax revenues will fall from the decrease in output and incomes, however sales tax revenues may increase if damaged goods are being replaced. If tax revenues decrease overall, there must be either a reduction in government services or an increase in public debt. Public disaster assistance is another cost for government.

To examine the impact of a flood in a city and the subsequent recovery, we develop a dynamic multi-sector computable general equilibrium (CGE) model. A representative firm for each sector uses capital, labour and intermediate goods from other sectors as inputs. Capital and labour are sector-specific.[4] New capital for each sector is produced from a fixed bundle of goods (mostly construction). Forward looking households choose their stream of consumption, making investment endogenous. The Armington assumption is applied so that imports are imperfect substitutes for domestic goods. The model is calibrated to a balanced growth path. The flood is modelled as a shock to the capital stocks of the representative firms.[5] Consistent with a balanced growth model, the economy rebuilds the capital stock through investment and converges back toward the balanced growth path over time.

In this paper we consider the impact of a flood in Metro Vancouver,[6] a metropolitan area

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[2]Another potential economic effect may be to change beliefs about flooding resulting in changes in prices, including insurance premiums. However, that is not considered in this paper.

[3]Furthermore, people who live in the flooded area may be unable to travel to work even if their workplace is physically unaffected by the flood.

[4]We are interested in near-term effects and use a 3-month timestep. It would be unrealistic for capital and labour to be able to flow freely between sectors over short time horizons. Sensitivity analysis is performed on the labour immobility.

[5]We ignore the losses *during* the flood period due to the unavailability of capital and labour because we focus on the long-term effects caused by capital damage.

[6]Metro Vancouver is made of up 23 jurisdictions, one of which is the City of Vancouver. In this paper all references to "Vancouver" or "the city" refer to Metro Vancouver, unless otherwise indicated.

with about 2 million people on Canada's Pacific coast.[7] Vancouver has been identified as the 11th most vulnerable coastal city in the world in terms of potential damage to capital from flooding (Hallegatte et al., 2013). It is located on land that includes the delta of the Fraser River. About 20% of the population and considerable economic activity are located in the flood plain, and are protected by dikes. There have been two very severe floods in the last 125 years, in 1894 and 1948. With climate change expected to cause sea level rise, the severity of flooding is expected to increase. The region has a diversified economy and had a GDP of roughly $110B CDN in 2010.

We consider a flood scenario for the lower Fraser Valley causing total capital damage in Metro Vancouver of $14.6 billion (in our baseline scenario). Transportation and Warehousing are most severely impacted, followed by Manufacturing and Wholesale Trade. We find that the GDP loss relative to a scenario with no flood is 1.9% ($2.07B) in the first year after the flood, 1.7% ($1.97B) in the second year, 1.5% ($1.70B) in the fifth year and 1.1% ($1.42B) in the twentieth year. We also find that the losses tend to scale approximately linearly with the damage rate. In our baseline scenario, exogenous payments are made in the amount of the damages. These payments represent insurance payouts and disaster assistance.[8] We compare the baseline scenario to a situation with no payouts and find little impact on GDP, however there is a significant impact on welfare.

Aside from ex post surveys, three main approaches have been used to quantify the economic impacts of disasters: econometric techniques, input-output modelling and computable general equilibrium modelling (CGE). Guimares et al. (1993) used an econometric approach to estimate the damages in South Carolina from Hurricane Hugo. They began by estimating the relationship between the economies of South Carolina and the entire United States. They then compared South Carolina's economic performance in the aftermath of Hurricane Hugo to its simulated performance (without hurricane) based on that of the entire U.S. economy. The difference was attributed to losses caused by the hurricane. Xiao (2011) used a similar approach to estimate the cost of flooding in the midwestern U.S. in 1993. Strobl (2010) studied the impact of hurricanes on economic growth in U.S. coastal areas. However, such approaches are backward-looking and would be of limited value in cases such as Vancouver where the most recent severe flood was in 1948. Also, in order to answer counter factual questions regarding

[7] This work is part of the Coastal Cities at Risk Project which is an interdisciplinary study of flooding in Vancouver, Manila, Bangkok and Lagos.

[8] In Canada, both provincial and federal governments provide assistance in the event of natural disasters. Provincial governments take the lead but in the event of a large disaster have backup from the federal government under the Disaster Financial Assistance Arrangements (DFAA, n.d.), instituted in 1970. A province may request federal assistance when eligible expenditures exceed $1 per capita (based on provincial population). The rate of compensation rises with the extent of the disaster. For costs between $1 and $3 per capita, DFAA pays 50%, from $3 to $5 it covers 75%, and above $5 per capita it pays 90%.

proposed adaptation measures, a model based on economic theory is required.

Modelling[9] the economic impacts of disasters is still a relatively undeveloped area of research. Cochrane (1974) published one of the first studies modelling the economic impact of natural hazards when he examined the potential impact of a California earthquake. His approach, which has become the most widely adopted in the study of natural disaster impacts, used an input-output model. Input-ouput models had been used in a variety of settings before being adopted for natural disasters. This included the impact of *man-made* disasters since World War II (Rose, 2004). Boisvert (1992) and Cochrane (1997) developed models of earthquake impacts that allow for a more flexible treatment of imports, as in the event of a disaster it is normal for imports to the affected region to increase as local production is disrupted.[10] Cochrane's approach has been incorporated into the HAZUS model developed by the Federal Emergency Management Agency in the U.S. (FEMA, 2012), which was initially applied to earthquakes and later extended to flooding. In this model, specific sectors' production is diminished by the disaster, but imports, exports and employment are able to adjust to make up for changes in supply and demand. The level of adjustment is constrained so that production losses are not all immediately recovered.

Hallegatte (2008) used an input-output approach to study the impact of Hurricane Katrina. A key innovation was to model damages as a shock to the capital stock, and the subsequent recovery as the rebuilding of that capital stock. Jonkman et al. (2008) used a detailed database to determine direct losses for flood scenarios in the Netherlands, with an input-output type model to quantify the output losses. Similar work has been done for Mumbai by Ranger et al. (2011). Most recently, Hallegatte et al. (2013) applied the approach pioneered in Hallegatte (2008) to study the possible future impacts of coastal flooding on 136 cities worldwide under sea level rise caused by climate change.

There are downsides to input-output modelling such as its linearity, rigidity and lack of behavioural content. For example, input-output models do not allow for substitution between different goods in consumption or between capital and labour in production. Furthermore, the loss of capital after a disaster is likely to drive up demand for investment to replace what was damaged. In a market economy, the distribution of investment across sectors should depend on each sector's marginal product of capital. Any attempt to incorporate some of these features into an input-output model requires ad hoc assumptions that do not conform to an underlying theory, muddying the interpretation and robustness of the results. For these reasons, an increasing number of studies have used computable general equilibrium (CGE) models to study the

[9] Here we differentiate models based on underlying economic theory from reduced form regression models.

[10] In our model imports decrease as a result of the flood because the drop in incomes is not fully compensated for by disaster assistance, and thus the local economy cannot afford more imports.

economic impacts of disasters. Rose and Guha (2004) used a CGE model to study the impact of the loss of electricity due to an earthquake. Rose and Liao (2005) and Berrittella et al. (2007) followed with studies of disruptions in the water supply. Tsuchiya et al. (2007) and Tatano and Tsuchiya (2008) used a multi-region CGE model to quantify the economic impacts earthquake damage to transportation networks in Japan. Jonkhoff (2009), Pauw et al. (2011), Haddad and Teixeira (2013) and Carrera et al. (2015) applied the CGE approach to study the impacts of flooding in the Netherlands, Malawi, São Paulo Brazil and the Po Valley of Italy, respectively. Other researchers used CGE to predict the economic effects of sea level rise (see Pycroft et al., 2015, and the references provided therein).

This paper presents the first use of a *dynamic* CGE model to study the economic impacts of flooding. This allows us to study not just the immediate impact of the flood, but also the recovery process. Furthermore, the calibration approach offers a flexibility that would allow the model to be implemented at a variety of scales and in many different countries. We present new data derived for Metro Vancouver in order to perform the calibration exercise in this paper.

In some ways flooding lends itself very well to economic modelling because we can predict the physical damage based on a spatial flood scenario; damages from an earthquake can be unevenly distributed across a region and differ considerably depending on the source, size and other characteristics. Thus we do not have to consider limited scenarios like disruptions in only electricity or water. Damages in our study can be based on specific flood scenarios, which can respond to various adaptation measures, and impact every economic sector. We use the recovery mechanism from the input-output model of Hallegatte (2008): investment using local production and imports rebuilds the capital stock. However, our CGE model innovates by allowing the pattern and speed of recovery to be determined endogenously. Specifically the level of investment is determined by a representative household choosing its lifetime stream of consumption to optimize welfare and new capital will be allocated to sectors based on its marginal products of capital. Furthermore, we examine how damage payouts (insurance and assistance) affect economic recovery.

The rest of the paper is organized as follows. Section 3.1 details the model. Section 3.2 describes Metro Vancouver, the local economy and its vulnerability to flooding. Section 3.3 outlines the data, section 3.4 presents simulation results and section 3.5 concludes.

3.1 The Model

The city's economy is modelled with a multi-sector balanced growth model. Each sector uses capital, labour and intermediate goods as inputs to production. The good produced by each sector is combined with an imperfectly substitutable import to create an Armington good. The

Armington goods can be consumed by the household or government, invested, used as an intermediate in production or exported. The household - and government - each optimize their stream of consumption over an infinite horizon. The model is used to chart the effects of an unexpected flood that acts as a negative shock to the capital stock.

3.1.1 Production

In each sector, capital and labour (effective units) are combined with intermediate (Armington) goods to produce domestic goods:

$$Y_t^i = F_t^i(\{\tilde{Y}_{it}^j\}_{j\in J}, K_t^i, L_t^i) \tag{3.1}$$

Here, Y_t^i is the domestic output in sector i in time period t, $F_t^i(\cdot)$ is a nested CES production function, $\tilde{Y}_{it}^j$ is the intermediate good from sector j used to produce good i, K_t^i is capital and L_t^i is labour. The nesting structure is shown in figure 3.1. The firms also pay sector-specific sales tax rates on intermediate inputs, τ_{BST}^i, and sector-specific business income tax rates on capital income, τ_{BIT}^i.[11]

Capital and labour are sector specific. Since we are most interested in the most severe impacts of the flood, we are focused on the first few years following the event. Over this time-frame we do not expect labour, and especially capital, to be very substitutable across sectors. Note that new capital can be allocated to any sector according to demand. We also perform a sensitivity test where we allow labour to be mobile.

The domestically produced goods are combined with imports to produce Armington goods:

$$\tilde{Y}_t^i = H^i(Y_t^i, M_t^i) \tag{3.2}$$

M_t^i is an imported good and H^i is a CES function. The Armington goods are used as intermediate inputs or in final demand. The production structure is shown in figure 3.1.

3.1.2 Household

The household consumes a good that is a composite of Armington goods:

$$c_t = g(\{\tilde{c}_t^i\}_{i\in J}) \tag{3.3}$$

Here, c_t is the consumption good and $g(\cdot)$ is a Cobb-Douglas function aggregating Armington goods $\tilde{c}_t^i$. The household is endowed with sector-specific labour (effective units), $\{l_t^i\}_{i\in J, t\in\{0,\infty\}}$,

[11] BST stands for business sales tax; BIT stands for business income tax.

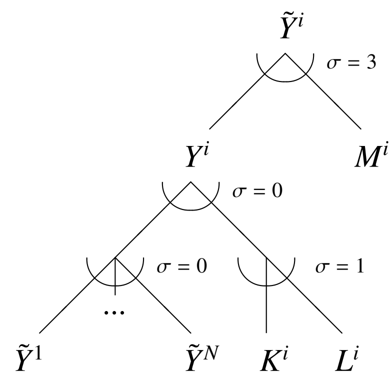

Figure 3.1: Production structure.

and initial capital, $\{k_0^i\}_{i\in J}$. Given prices, the representative household chooses its stream of consumption and investment to maximize utility subject to its budget constraint:

$$\max_{\{c_t, i_t^i\}_{t\in[0,\infty)}} \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{3.4}$$

subject to

$$\sum_{t=0}^{\infty}\left[p_t(1+\tau_C)c_t + \sum_i p_t^{I^i}(1+\tau_I)i_t^i\right] = \sum_{t=0}^{\infty}\sum_{i=1}^{N}\left[(w_t^i - \tau_L)l_t^i + (R_t^i - \tau_K)k_t^i\right] \tag{3.5}$$

$$k_{t+1}^i = (1-\delta^i)k_t^i + i_t^i \tag{3.6}$$

We shall use the functional form $u(\cdot) = \ln(\cdot)$ for the utility function. β is the discount rate, which is between 0 and 1. p_t is the price of the composite consumption good, $p_t^{I^i}$ is the price of the investment good, w_t^i is sector-specific wages and R_t^i is the sector-specific return to capital. i_t^i is sector-specific investment and δ^i is the depreciation rate in sector i. τ_C and τ_I are rates of sales tax on consumption and investment goods, while τ_L and τ_K are tax rates on labour and capital incomes. Note that the p_t's are intertemporal prices and thus embody discounting in the budget constraint.

3.1.3 Investment and trade

Investment is sector-specific, however the bundle of goods that comprise the investment good is a fixed bundle across all sectors:

$$i_t^i = N \min_{j\in J}\{b_j \tilde{Y}_{i_t^i}^j\} \tag{3.7}$$

N is the number of sectors, $\tilde{Y}^j_{i^i_t}$ are the goods allocated to investment and b_j are the coefficients determining the composition of the investment bundle. In our simulations of Metro Vancouver, investment is primarily made up of construction services and manufactured goods.

Exports generate "foreign currency", F_t. The amount of foreign currency generated from the sale of good X^i_t is denoted by $F^{X^i}_t$. Foreign currency can be used to purchase any foreign good; the amount of foreign currency used to purchase import M^j_t is denoted by $F^{M^i}_t$.

$$X^i_t = F^{X^i}_t, \qquad p^i_t X^i_t = p^F_t F^{X^i}_t \tag{3.8}$$

$$M^i_t = F^{M^i}_t, \qquad p^{M^i}_t M^i_t = p^F_t F^{M^i}_t \tag{3.9}$$

The above equations impose that the prices of all exported goods move together along with the prices of imported goods and the exchange rate, p^F_t. This establishes that there are world prices that cannot be changed by the local region (small open economy). However, if a good is not exported then its price can move freely. This occurs because domestic demand is so strong for the local good that it good cannot be met at world prices; recall that the equivalent foreign good is not a perfect substitute because of the Armington assumption.[12] The trade deficit, D_t, is exogenously supplied to the model for each time period.

$$\sum_i M^i_t = \sum_i X^i_t + D_t \tag{3.10}$$

3.1.4 Government

The government sector is an amalgam of all levels of government in the city studied. It levies labour and capital income taxes and sales taxes and uses the revenue to purchase goods and services, that is to "consume".[13] We assume that the government has a utility function defined over its stream of consumption, and maximizes it subject to its intertemporal budget constraint. In each period the government consumes a bundle of Armington goods:

$$G_t = N \min_{j \in J} \{ b^G_j \tilde{G}^j_t \} \tag{3.11}$$

The coefficients, b^G_j, determine the ratio of goods in the bundle. We assume the government bundle has fixed proportions because we do not believe policy regarding the relative provision of government services, like education and healthcare, is affected by relative price changes.

[12] In our simulations it is rare for exports to be shut down.

[13] We do not include disaster assistance payments in the government budget or provision of services. We treat that as an exogenous endowment of foreign exchange from outside the local municipality.

The government problem is given by:

$$\max_{\{G_t\}_{t\in[0,\infty)}} \sum_{t=0}^{\infty} \beta^t v(G_t) \tag{3.12}$$

subject to

$$\sum_{t=0}^{\infty} p_t^G G_t = \sum_{t=0}^{\infty} \left[T_t^L + T_t^K + T_t^{Sales} \right] \tag{3.13}$$

Again, we use the functional form $v(\cdot) = \ln(\cdot)$ for the utility function, with discount factor β (the same value as the household). p_t^G is the price of the government consumption bundle and T_t^{type} are the different types of tax revenues collected (labour and capital income taxes plus sales taxes). The amounts of tax revenue are determined by exogenous tax rates. That is, there is a tax rate for labour and capital (varying by sector for capital) and sales tax rates on intermediate inputs for each sector plus household and investment purchases (more detail is given in section 3.3).

We have left tax rates exogenous since changes in such rates are relatively infrequent. The level of government spending in each year is endogenous, however, and government has a choice about how to adjust its spending level from period to period in the face of the altered prices that may arise in the wake of a flood. How it reacts depends partly on the specification of the function $v(\cdot)$. Here we have assumed *log* utility, which gives constant expenditure shares across periods. However, a utility function that would generate less elastic demand could be assumed if that was determined to be more realistic. In addition, the coefficients in (3.11) could be allowed to change as a result of a disaster (perhaps accounting for the provision of disaster related services). While incorporating such features is technically possible, we do not pursue these aspects in this paper since work along these lines requires very careful study of how government spending actually is affected by flooding, which is outside the scope of this paper.

While the explicit government sector in our model may be considered rather passive in the face of flooding, the main public sector response to flooding, which is external, is captured separately. As noted earlier, we have assumed that all capital damage is compensated for through insurance payouts or public disaster assistance. Since little flood insurance is available in Canada, this means that a large amount of external disaster assistance from the provincial and federal governments is being assumed, as is realistic.[14] We study the impact of that assistance

[14]Repairs or replacement of capital owned by households, small businesses or provincial or municipal governments are all eligible for federal assistance under the Disaster Financial Assistance Arrangements (DFAA, n.d.). While assistance to large businesses and crown corporations is not covered by the federal plan, provinces are free to assist those organizations if they wish to do so. Thus the assumption of very large government response via

in our simulations, thereby capturing the main expenditures of government in mitigating the economic impacts of flooding.

3.1.5 Market clearing

The goods, capital and labour markets all clear:

$$\tilde{Y}^i_t = \sum_{j=0}^{J} \left[\tilde{Y}^j_{it} + \tilde{Y}^j_{i^i_t} \right] + X^i_t + \tilde{c}^i_t + \tilde{G}^i_t \tag{3.14}$$

$$K^i_t = k^i_t \tag{3.15}$$

$$L^i_t = l^i_t \tag{3.16}$$

3.1.6 Solution to the model

An equilibrium given an initial capital stock, $\{k^i_0\}_{i \in J}$, is defined as the set of prices and quantities in the model such that given prices: firms maximize profits; the household and government maximize utility subject to their budget constraints; trade and investment satisfy the equations in section 3.1.3; and all markets clear (goods, capital, labour, trade including deficit).

The equilibrium solution converges toward a balanced growth path.[15] That is:

- The quantities Y^i_t, $\tilde{Y}^j_{it}$, K^i_t, M^i_t, X^i_t, c^i_t, i^i_t, G_t, T^{inc}_t, T^{Bus}_t and T^{Sales}_t all have growth rates of g as $t \to \infty$;

- The prices p^i_t, $\tilde{p}^i_t$, p^F_t, $p^{M^i}_t$, R^i_t, w^i_t, $p^{I^i}_t$ and p^G_t all have growth rates of $\frac{\beta}{1+g} - 1$ as $t \to \infty$ (for log utility);[16]

- $R^i_t \to R$ for all i as $t \to \infty$; $r = R - \delta$.

Note that due to the constant growth rates, quantities and prices have constant ratios in the limit. In the quantitative exercise, we assume that the economy is following the balanced growth path prior to the flood in order to calibrate the model. Once the parameters are determined, we perform counter-factual analysis of flood scenarios.

disaster assistance is realistic.

[15] Note that the effective units of labour, L^i_t, grow at the exogenously supplied growth rate, g. For details of balanced growth, see Acemoglu (2009).

[16] Note that $\tilde{p}^i_t$ is the price of the Armington good i.

3.2 Scenario - Vancouver

Metro Vancouver is a large urban area that is of considerable importance to the Canadian economy. It is situated at the mouth of a major river, the Fraser. A significant portion of the city is on the river's floodplain, including the large delta on which the cities of Richmond and Delta are mainly located (see figure 3.2). The Fraser tends to flood in the spring, as a result of snow melt in the mountains and spring rains. But the area is also threatened by coastal flooding. Weather systems from the Pacific sometimes cause large storm surges on the coast and some distance up the river. While the area is protected by dikes, dike breach can occur and is difficult to repair under flood conditions. The seriousness of the threat is expected to increase as sea level rises due to climate change. Study of Vancouver is facilitated by its inclusion in a large interdisciplinary research project on Coastal Cities at Risk funded by Canada's three major research granting agencies. The approach used here could be adapted to other cities facing flood risk.

It is unfortunately difficult to get many standard economic indicators, such as output by industry, and imports or exports for geographical areas smaller than a province in Canada. GDP numbers were not available by city until experimental estimates were released in November 2014 (Brown and Rispoli, 2014). This leaves knowledge of the economic structure of any city in Canada, and even its largest metropolitan areas, incomplete. There is information on the size and composition of the labour force, both from the monthly Labour Force Survey and, in more detail from the decennial census and the supplementary census conducted halfway between the main censuses. In section 3.3, we use the 2006 census National Household Survey (Statistics Canada, 2006) to estimate that 86% of employment was in the service sector in 2010. Just 10% was in manufacturing, only 1.1% in agriculture and other primary activities, and 0.7% in utilities. Construction accounted for 2.5% of the labour force. The largest labour force in the service sector belonged to retail trade (12%); professional scientific and technical services made up 10%, while finance and real estate accounted for 8% of the workforce. For more detail see Table 3.1. Assuming productivity within industries was the same in Metro Vancouver as in the province as a whole, we estimate Metro Vancouver's GDP to have been $110 billion in 2010 (see section 3.3 for details), which represents about half of the provincial total.[17]

The industrial composition of Metro Vancouver as a whole does not provide a guide to the activities that would be directly affected by flooding since the representation of industries in the floodplain is somewhat different. In the floodplain areas, transportation and warehousing and agriculture are relatively more important. Vancouver International Airport, for example,

[17]Brown and Rispoli (2014) estimate GDP for Metro Vancouver at $103 billion in 2009. Since GDP for B.C. as a whole grew 5% in 2010, our estimate of $110 billion for Metro Vancouver's GDP in 2010 is well aligned with the Statistics Canada number. We also match their service sector share of value added, 83%.

is built on Sea Island at the mouth of the Fraser where ground level is about a metre below sea level at high tide. Some of Port Vancouver's extensive facilities are also located in the floodplain. The agricultural sector includes expensive facilities such as very large greenhouse complexes in Delta and Surrey that are vulnerable to flooding.

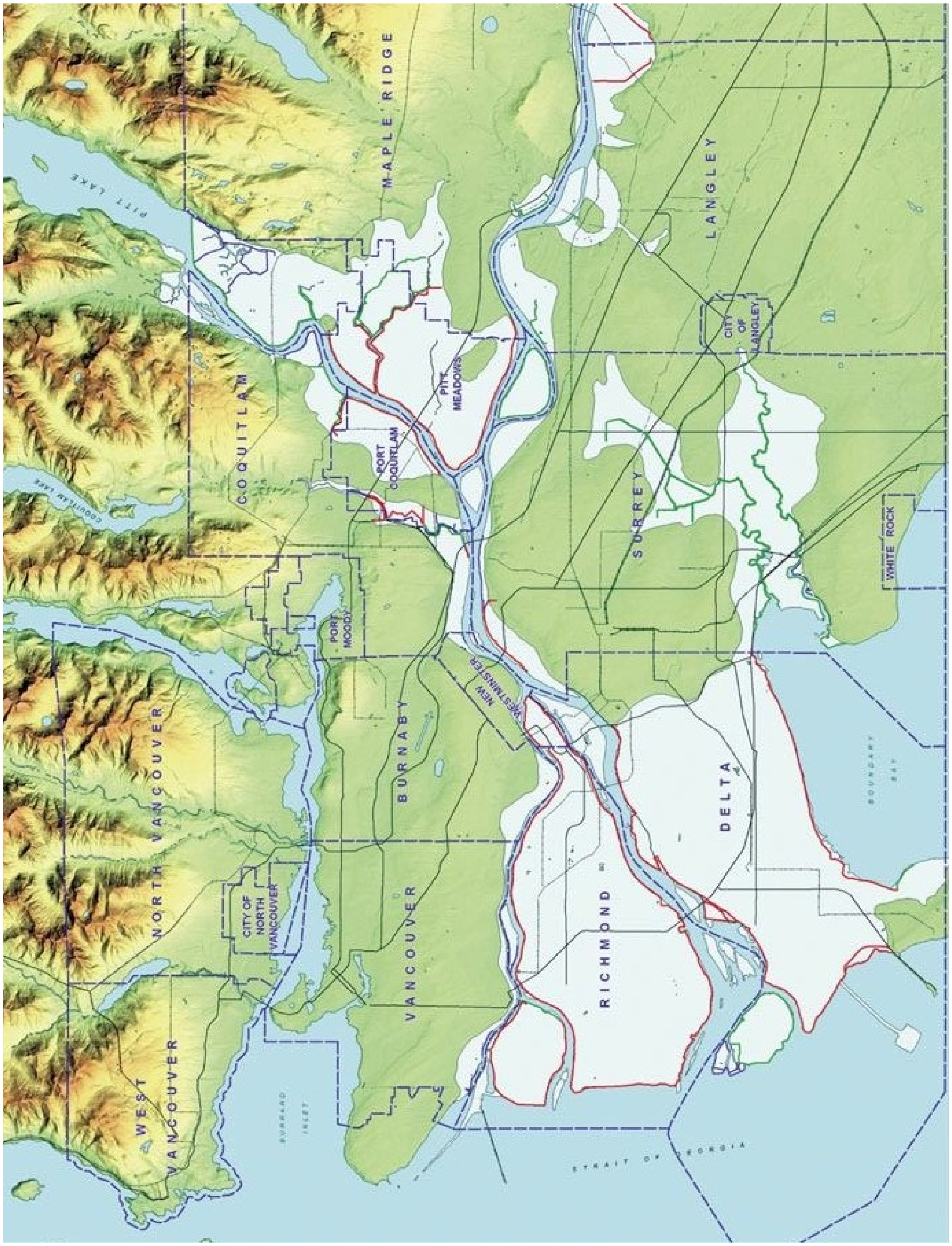

Figure 3.2: Metro Vancouver floodplain map (white indicates floodplain). Source: Fraser Basin Council (n.d.).

The importance of Vancouver's port and airport has been analyzed in recent economic impact studies. While we discount the estimates of indirect jobs and output that are a common feature of such studies, the numbers they provide on direct impacts are helpful. In 2012 it is estimated that Port Vancouver provided 38,000 jobs directly and contributed $3.5 billion to GDP directly (InterVISTAS Consulting Inc., 2013). Vancouver International Airport was estimated to provide 23,614 direct jobs and to contribute $1.8 billion to GDP directly in 2010 (Economic Development Research Group, Inc., 2011). Using these numbers, the port and airport together would account for 5% both of Metro Vancouver's labour force and its GDP in 2010.

Other transportation aspects are also important. Canada's major road and rail networks originate/terminate in Vancouver, and there are also important links to the U.S. The Trans Canada highway and the main roads to the U.S. pass through the floodplain, as do the CPR, CNR, the Southern Railway and the BNSF railway from the U.S. Highway 99, one of the most important north-south road links, passes through the Massey Tunnel under the Fraser River, close to its mouth, and would be vulnerable in a major flood. For many kilometres the main line of the CNR follows the south bank of the river, and the CPR has a significant stretch that runs close to the north bank. The BNSF hugs Boundary Bay from its entry into Canada to Surrey, and delivers large volumes of U.S. coal to the Roberts Bank coal export terminal at Tsawwassen, reportedly the busiest coal terminal in North America. Closure of these road and rail links for any significant period of time would cause costly interruption/reduction in the supplies of food, other consumer goods, and industrial inputs in Metro Vancouver. It would also impose costs spread over B.C., Western Canada, and the Northwest U.S. Impacts on the U.S. coal industry, for example, could be serious as coal exports have been banned from most U.S. west coast ports.

There have been two especially severe floods on the Fraser River in the last 125 years. The first occurred in May 1894 and caused wide inundation but little damage in economic terms since the area was still relatively undeveloped. At that time use of the floodplain was largely confined to agriculture and fishing. By the time of the next major flood, in May 1948, the situation had changed, with the development of light industry, sawmills and other enterprises, as well as a sizable increase in population. It is recorded that 10% of the Fraser Valley, in total 200 square kilometres, was flooded. There were 10 fatalities, 16,000 people were evacuated, 3,000 buildings were destroyed, and 82 bridges were washed out. Total damages are estimated at $210 million in 2010 dollars (Fraser Basin Council, n.d.; BC Ministry of Forests, Lands and Natural Resource Operations, n.d.). It has been estimated by Canadian agencies that a repeat of the 1948 flood today would cause "several billions" of dollars in damage to the City of Richmond alone, and "tens of billions" of dollars of damage in total to communities on the

Fraser River. Hallegatte et al. (2013) apply a uniform methodology to estimate the flood risks faced by 136 coastal cities around the world. They rank Vancouver as the city with the 11th greatest exposure of capital to a one hundred year flood, estimating that in 2005 it had exposure of $33.4 billion.[18] If 25% of this capital were destroyed in such a flood, damage would be $8.4 billion, agreeing roughly with the level of damage assumed here (see section 3.4).[19]

While a flood of equal magnitude to that of 1948 has not yet recurred, this remains a constant possibility. After the 1948 flood, dikes were constructed or raised to a height that would protect against another flood of that order. There are currently over 600 km of dikes and 100 pumping stations (Fraser Basin Council, n.d.). However, much of the diking was originally designed to protect farmland, whereas it now serves urban areas, which may need a higher standard of protection. Also, climate change is expected to result in sea level rise (SLR); 26 cm to 82 cm in the 21*st* century (IPCC, 2014). The mid point of this range would bring high tide levels to 1.5 metres above ground level in the lower reaches of the Fraser. Further factors that may exacerbate flooding in the future are land subsidence, which is ongoing at a slow but steady rate, higher storm surges from the sea due to more extreme weather, and stronger/higher wave action as the waters being held back by the dikes deepen.

Here we model the economic impacts of a flood of the 1948 dimension assuming a "worst case" scenario in which dike breaches occur in a number of locations, leading to general inundation of the flood plain. We assume the population, assets, and economic activity seen in 2010, the most recent year for which the necessary data are available. Based on the floodplain map, we assume the areas flooded are 100% of Richmond, 70% of Delta, 5% of the City of Vancouver, 10% of Surrey, and 5% of Burnaby. Effects on some smaller communities, such as Coquitlam, are not considered. In our central case it is assumed that 25% of the capital - buildings, machinery and equipment - in each area is destroyed. This results in a loss of 4.4% of Metro Vancouver's total capital stock, with the greatest damage being 10% in the transportation and warehousing sector. Sensitivity testing is done assuming lower and higher levels of capital damage.

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[18] Hallegatte et al. (2013) also estimate that the expected annual cost of flooding as of 2005 was $107 million for Vancouver. Considering that floods that cause more than a few million dollars in damage have not been experienced since 1948, this figure likely reflects a forecast in which infrequent major floods cause billions of dollars of damage.

[19] In related exercises, some have estimated the damage that would be done by sea level rise (SLR) if flood defences are not improved. Given the SLR typically predicted for the next century one would expect inundation similar to what would be caused by a one hundred year flood. The National Roundtable on the Environment and the Economy (2011) estimated that for Canada SLR would cause between $1 and $8 billion in annual damage by 2050, based on a rise in sea level ranging from 0.28 to 0.85 metres. Harford (2014) claims that a 1 metre SLR could cause $12 billion in damage for the city of Vancouver alone.

3.3 Data

The model is calibrated to the Metro Vancouver economy assumed to be following a balanced growth path. That is, in the absence of a flood all inputs and outputs are assumed to grow at a constant annual growth rate, g, which we set at 2%; this determines other key parameters in the model. When the flood hits, the capital stock is shocked and the economy is knocked off the balanced growth path at $t = 0$ and asymptotically converges back toward the balanced growth path over time.

The most important data needed for a multi-sector model is a social accounting matrix (SAM) with details on sector-specific intermediate inputs, labour, capital and taxes, as well as final demand (private consumption, government consumption, investment, imports and exports). These data are used to determine share parameters for the sector-specific production functions, the consumption bundles and the investment good, as well as tax rates and trade shares. The starting point for constructing our SAM is the 2010 British Columbia input-output table and final demand table (Statistics Canada, 2010). However, we require this data at the municipal level. We use the method of Heijman and Schipper (2010), briefly explained in the next subsection, to derive the Metro Vancouver social accounting matrix. This requires output by sector at the municipal level. We do not have this data, however we have employment by sector at the municipal level from the 2006 census (Statistics Canada, 2006). We use BC Stats (n.d.) employment data to adjust the employment by sector for the year 2010. We assume sectoral output-employment ratios are the same in Metro Vancouver as the rest of B.C. to estimate output by sector in Metro Vancouver.

To complete our SAM we need data on direct taxes, which is not provided in the B.C. input-output table. Therefore, it is assumed that the shortfall between government spending and revenues is covered by taxes on labour and capital income. This is explained in more detail below.

Metro Vancouver comprises 23 jurisdictions: 21 municipalities, one electoral area (University of British Columbia) and one treaty First Nation. The census provides sectoral employment data for each municipality. Assuming sectoral capital-employment ratios are constant across municipalities we can estimate the division of each sector's capital stock across municipalities. This allows us to incorporate the spatial dimension of damage scenarios.

3.3.1 Local input-output table

The B.C. 2010 symmetric input-output table is comprised of 25 private business sectors, 6 government sectors and 1 non-profit sector. The table also provides spending on labour income, operating surplus (which we consider to be capital income), taxes and subsidies.

We construct a local input-output table for Metro Vancouver in two stages (the actual tables are given in Appendix A). First we estimate total output by sector. Then we fill in the flows of intermediate inputs by an imputation procedure.

To obtain estimates for local sectoral output, we calculate each sector's output-employment ratio for B.C. as a whole and then multiply Metro Vancouver's sectoral employment numbers[20] by these ratios. If output-employment ratios differ significantly between Metro Vancouver and B.C. as a whole there will be error in our output estimates. However, since we are accounting for sectoral differences, and Vancouver makes up half of the B.C. economy, we do not believe the error would be very large.[21] Table 3.1 shows our estimates of employment, output and value added by sector in Metro Vancouver for 2010.[22] Note that the sectors expected to suffer the highest rate of capital damage - transportation and warehousing and agriculture - make up a relatively small fraction of the economy but still account for output of $14.8B and value added of $7.4B.

[20]The most reliable sectoral employment numbers are provided by the census. We adjusted the 2006 census figures for Vancouver to a 2010 basis by imposing the overall growth of Vancouver employment (8.25%) and assuming the same sectoral shifts as shown for the province as a whole in the BC Stats (n.d.) employment report.

[21]One indication of accuracy is agreement between the goods vs. services split in our numbers and those in Brown and Rispoli (2014). We each get an 83% service share.

[22]We combine some of the 32 sectors in the B.C. input-output table to get the sectors listed in the table. This is necessary because Vancouver sectoral employment numbers are only available for 20 sectors.

Sector	Employment	Output ($ million)	Value Added ($ million)
B11 Agriculture, forestry, fishing and hunting	8,110	1,599	515
B21 Mining and oil and gas extraction	3,774	3,921	2,404
B22 Utilities	6,830	2,677	1,358
B23 Construction	26,136	15,430	13,284
B31-B33 Manufacturing	105,345	20,901	1,546
B41 Wholesale trade	62,105	8,017	5,004
B44-B45 Retail trade	126,441	9,126	7,270
B48-B49 Transportation and warehousing	48,598	13,153	6,881
B51 Information and cultural industries	36,448	7,807	4,045
B52-B53, B55 Finance, insurance, real estate	85,605	42,295	28,366
B54 Professional, scientific and technical services	103,248	10,675	4,146
B56 Administrative and support, etc.	38,133	4,375	367
B61 Educational services (private)	3,829	494	351
B62 Healthcare and social assistance (private)	46,397	4,199	2,108
B71 Arts, entertainment and recreation	24,009	1,839	1,417
B72 Accommodation and food services	75,645	5,780	4,630
B81 Other services (except public administration)	52,791	5,886	4,581
G61 Educational services (public)	82,266	6,321	6,142
G62 Healthcare and social assistance (public)	74,535	4,255	3,968
G91 Public administration	48,062	13,002	11,692
Total	1,058,311	181,750	110,074

Table 3.1: Metro Vancouver employment, output and value added (GDP) for 2010.

3.3.2 Demand table

In the model we have five final demand categories: private consumption, government consumption, investment, imports and exports (the derived final demand table for Metro Vancouver can be found in Appendix A). The final demand table in the industry accounts has a more disaggregated detail. We combine the detailed categories of final demand from the latter table into our five broad demand categories as follows:

- Private consumption: household consumption and non-profits;
- Government consumption: government consumption;
- Investment: all construction, machinery and intellectual property columns;
- Exports: international and inter-provincial exports, re-exports and inventory additions;
- Imports: international and inter-provincial imports, and inventory withdrawals.

Local total demand and intermediate demand are determined by the input-output table.[23] Local *final* demand is the difference between total demand and intermediate demand. The ratio of consumption of each good to GDP is calculated for the province as a whole, then those ratios are assumed to hold for Metro Vancouver giving household consumption by good at the local level. To determine the distribution of government consumption, we multiply the province level government consumption by sector by the fraction of B.C. workers who are employed in Metro Vancouver (54%). We do this because we expect government services to be more closely related to employment (population) levels than to income levels. The local investment and exports are determined by multiplying province-level values by the fraction of that industry's production concentrated in Metro Vancouver. For example, 20% of B.C.'s agricultural output is in Metro Vancouver, therefore we assume 20% of agricultural investment goods and exports are from Metro Vancouver. Imports are treated in a similar fashion, except using only the local fraction of *domestic* demand.

To this point, we have not yet accounted for intra-provincial trade (on which there is no data). Furthermore, using the above approach to get the local final demand table, there are small residual differences between the sum of total demand in each sector/good and the total demand needed to ensure that all output is sold (zero profits). The residual could arise either due to (inescapable) errors in the imputed amounts for consumption, investment, and exports and imports with the rest of the world and Canada, or because we have ignored intra-provincial trade. Since we have no way of knowing what errors may have been made in the imputations we

[23]For zero profits in each sector, total demand is equal to the total cost of all inputs.

attribute the entire residual to intra-provincial trade. Our estimates of net intra-provincial trade are therefore given simply by the residual. Gross intra-provincial trade flows are estimated using the following procedure. Consider two extreme cases for gross trade flows:

1. Minimum trade: Trade is in one direction - imports only or exports only. If the residual is negative there will be intra-provincial exports; if it is positive then there will be imports. In either case the trade flow will be just enough to offset the residual.

2. “Maximum” trade: Each good produced in Metro Vancouver has a random chance of being consumed in Metro Vancouver or the rest of B.C., weighted by the demand for that good in the two places. This assumption dictates the amount of intra-provincial exports. Intra-provincial imports are the difference between the estimated intra-provincial exports and the residual.

The minimum trade case gives relatively small exports or imports across all sectors and is helpful in setting a lower bound. The “maximum” trade case gives the amount of intra-provincial trade that would occur, theoretically, if no additional transport or other costs were incurred when goods or services were traded intra-provincially rather than produced and used within Vancouver. Even more trade could occur if, for example, the first source of supply for all goods and services in the rest of the province was Vancouver and vice versa - but that is implausible.

To estimate intra-provincial trade flows, we start with case 2, which clearly implies too much intra-provincial trade since there are in fact additional transport costs of trading with the rest of the province rather than transacting only within Vancouver. This maximum total trade is then multiplied by a “trade coefficient”, where a coefficient of 0.25 would imply, for example, there is a quarter the trade of the maximum case.

We started with a baseline coefficient of 0.5, however in some sectors this results in a disproportionate level of intra-provincial trade compared to trade with the rest of the world and Canada. Consideration of characteristics of many sectors suggested a lower coefficient was needed, and we have used a value of 0.1 in most such cases (see the first column of Table 3.2). For finance, insurance and real estate, and for public administration we use a coefficient of 0.25. For manufacturing, which is highly trade-oriented, we use 0.75. For construction we expect very little trade and use a value of 0.01.

Note that for B.C., international trade is 50% of GDP and inter-provincial trade is an additional 41% of GDP. Our trade data is given in Table 3.2. For our Metro Vancouver estimates, international plus inter-provincial trade is 84% of GDP (compared to 91% for B.C.), and intra-provincial trade is an additional 44% of GDP. Trade differs considerably in importance across sectors, from a very low level in construction and some service industries like health and education, to a high level in transportation and warehousing and manufacturing. Note that total manufacturing exports (intra-provincial plus those to the rest of Canada and the world), at \$22.3B, exceed the manufacturing output of \$20.9B shown in Table 3.2. This reflects the high level of imports and re-exports of manufactured goods.

Sector	Trade coefficient	Intra-provincial			Rest of Canada and world		
		Total	Exports	Imports	Total	Exports	Imports
B11 Agriculture, forestry, fishing and hunting	0.5	1,285	530	-755	1,100	534	-566
B21 Mining and oil and gas extraction	0.1	584	324	-260	4,117	2,908	-1,209
B22 Utilities	0.1	241	138	-103	496	254	-243
B23 Construction	0.01	169	49	-120	67	20	-47
B31-33 Manufacturing	0.75	14,435	7,279	-7,156	45,333	14,987	-30,345
B41 Wholesale trade	0.5	2,406	1,774	-631	5,443	2,790	-2,653
B44-45 Retail trade	0.1	909	106	-803	1,962	1,368	-594
B48-49 Transportation and warehousing	0.5	4,905	2,795	-2,110	9,916	6,797	-3,119
B51 Information and cultural industries	0.5	2,202	1,597	-605	3,729	1,962	-1,766
B52-53, 55 Finance, insurance, real estate	0.25	7,670	5,880	-1,790	6,753	2,268	-4,484
B54 Professional, scientific and technical services	0.5	3,499	2,447	-1,053	5,039	2,981	-2,058
B56 Administrative and support, etc.	0.1	369	260	-109	2,372	1,120	-1,251
B61 Educational services (private)	0.1	44	20	-24	80	74	-6
B62 Health care and social assistance (private)	0.1	411	365	-46	96	21	-75
B71 Arts, entertainment and recreation	0.5	875	385	-490	910	453	-456
B72 Accommodation and food services	0.5	2,835	1,210	-1,625	3,725	1,961	-1,764
B81 Other services (except public administration)	0.1	528	209	-319	702	435	-267
G61 Educational services (public)	0.1	569	296	-273	391	198	-193
G62 Healthcare and social assistance (public)	0.1	416	105	-311	182	115	-66
G91 Public administration	0.25	3,815	134	-3,680	556	239	-317
Total		48,167	25,903	-22,263	92,969	41,485	-51,479

Table 3.2: Estimated Metro Vancouver trade with rest of B.C. and elsewhere ($M) in 2010.

3.3.3 Government and taxes

There are two types of taxes (and subsidies) given in the industry accounts data for British Columbia: taxes on products and taxes on production. We treat the taxes on products net of subsidies as sales taxes applied to intermediate and final goods.[24] We determine the tax rates for B.C. as a whole for intermediate inputs in each sector plus private consumption and investment, and apply them to Metro Vancouver. We treat the taxes on production net of subsidies as capital income taxes.[25] We determine the tax rates as a percentage of capital income in each sector for B.C. as a whole and apply them to Metro Vancouver.

The industrial accounts data does not include any direct taxes. As a result, the tax revenue (\$12.7B) falls significantly short of government spending (\$22.7B) for Metro Vancouver.[26] Therefore we calculate the average tax rate on personal income needed to cover the government deficit. The resulting (average) personal income tax rate is 12.8%, which is low because our analysis ignores pure transfers from the government to households. For modelling purposes, we divide this personal income tax burden between labour and capital income.[27]

3.3.4 Assumed parameter values

Several parameters must be set exogenously: the growth rate, the rate of depreciation and the elasticity parameters. Standard values are chosen for these parameters and sensitivity is tested in section 3.4.3. The growth and deprecation rates are used (along with the initial capital stock, initial investment and the tax rate on investment) to determine the interest rate (as described below). Key parameter values are given in table 3.3.

We assume the economy follows a balanced growth path (BGP), so we can use the growth rate to determine the interest rate along the BGP. From the local final demand table we know investment in the first period, I_0, and the capital earnings net of taxes, VK_0. We have also calculated the sales tax rate on investment goods, τ_I. Since $K_{t+1} = (1-\delta)K_t + I_t$ and $K_{t+1} = (1+g)K_t$ along the BGP, we get that $I_t = (\delta + g)K_t$. Furthermore, $VK_t = R_t K_t$, and along the BGP $R_t = (\delta + r)/(1+\tau_I)$ where r is the interest rate. Using $g = 2\%$, $\delta = 5\%$ and $\tau = 5.5\%$ along with appropriate values for I_0 and VK_0, we solve for $r \approx 7.6\%$. The discount factor is calibrated using the long run interest rate: $\beta = \frac{1}{1+r}$.

[24]We disregard taxes on exports and imports to simplify the model as the amounts are tiny.

[25]The major item in taxes on production is property tax. This category of tax also includes all other taxes levied on production or the assets used in production. It does not include taxes on business income which we treat as being included with direct taxes on capital.

[26]Recall that this includes the contribution to Metro Vancouver from all three levels of government.

[27]In dividing the personal income tax burden, we assume that capital income is taxed at half the rate applied to labour income. This is intended to reflect the sheltering of capital income through pension plans, RRSPs, TFSAs and the like, as well as the relief afforded by the 50% inclusion rate on capital gains and the dividend tax credit.

Table 3.3: Key parameters (fixed across sectors).

Parameter	Value	Notes
g	0.02	Growth rate.
δ	0.05	Rate of depreciation.
r	0.076	Interest rate.
β	0.929	Time discount rate.
$\sigma_{K,L}$	1	Elasticity of substitution between capital and labour.
$\sigma_{\tilde{Y}^i,\tilde{Y}^j}$	0	Elasticity of substitution between intermediate goods.
σ_{Y^i,M^i}	3	Elasticity of substitution between domestic and foreign goods.
σ	0	Elasticity of substitution between value added and composite good.
$\sigma_{\tilde{c}^i,\tilde{c}^j}$	1	Elasticity of substitution between consumption goods.
$\sigma_{\tilde{G}^i,\tilde{G}^j}$	0	Elasticity of substitution between government goods.
ϕ	1	Inter-temporal elasticity of substitution.

3.3.5 Flooding

We model the flood event as a shock to the sector-specific capital stock. Assuming that the capital-labour ratios in each sector are initially the same across municipalities, we can use the Census municipality-level sectoral employment data to estimate the distribution of the capital stock across municipalities. For example, we calculate that 12.5% of all agricultural workers in Metro Vancouver work in Delta, so we assume that 12.5% of the agricultural capital stock is located in Delta.

Next, for a flood scenario we determine what proportion of each municipality's capital stock is exposed. In this paper we consider a flood of the lower Fraser valley and use flood plain maps to approximate capital exposure in each municipality. Based on the flood map (see figure 3.2), we consider this to be a flood of 100% of Richmond, 70% of Delta, 10% of Surrey, 5% of the city of Vancouver and 5% of Burnaby.[28] Each sector's capital is exposed at the same rate *within* a municipality, however due to different distributions of capital across municipalities the exposure is heterogeneous across sectors when aggregated back up to the Metro Vancouver level. The distribution of exposure is given in figure 3.3.

The Transportation and Warehousing sector (BS48) is most exposed in percentage terms because the airport in located in Richmond and the region's largest seaport is located in Delta. The Manufacturing (BS31) and Wholesale Trade (BS41) sectors are also hit disproportionately hard. In terms of value, the Finance and Real Estate sector (BS52) is hit by far the hardest simply because it is an extremely capital-intensive sector.

Not all exposed capital is damaged. For our baseline scenario, we consider a damage rate

[28]These figures are based on both the amount of land area in floodplains and the urban density in those areas. There would be flooding in other municipalities but we do not include them as they are small or the flood areas are small and thus would have little impact on the results.

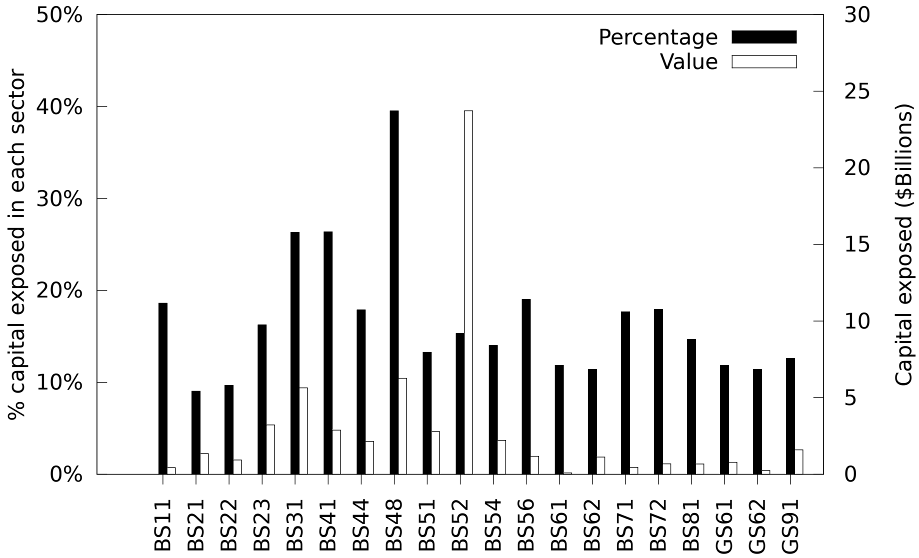

Figure 3.3: Aggregate capital exposed in percentage and value terms across industry.

of 25%. For example, we consider that 10% of Surrey's capital stock is exposed to the flood, but only 25% × 10% = 2.5% of the capital stock is damaged. In this paper we use the same damage rate across all municipalities. A plot of the damage distribution would be the same as figure 3.3 except at 25% of the magnitude.

3.4 Simulations

We simulate a flood of the lower Fraser River in Metro Vancouver, as described in section 3.3.5. We compare economic indicators, in particular GDP, from the flood scenario(s) to the baseline scenario with no flood. We assume that damages are completely covered by the government or private insurance. Specifically, the total damage is paid out over the course of two years with equal payments coming each time period. Since there is no money in the model, this is achieved through an endowment of foreign exchange. This approach captures the idea that the local economy is physically constrained in terms of available capital and labour, however it allows for an increase in imported goods.

The simulations are run using GAMS/MPSGE following the implementation of Paltsev and Rutherford (2004) for a dynamic growth model. A quarterly timestep is used out to 55 years after the flood. We focus on the near-term impacts of the flood but maintain a long time horizon so the model returns very closely to the balanced growth path by the end of the simulation.

We quantify economic losses from the flood and the degree of recovery at different points in time. We also examine sectoral and government impacts, as well as impacts on trade. The baseline scenario (25% damage rate) is discussed first, followed by a comparison with other damage rates (5%, 10%, 15%, 20%, 35%, 50%, 75% and 100%) to see how the results scale with level of damage. We also study the sensitivity of the results to the assumption that losses are fully compensated and to the assumption of no labour mobility.

3.4.1 Baseline scenario

In a balanced growth model, the long-run behaviour of the economy is determined by the parameters of the model and not the initial endowments. Therefore when the capital stock is shocked it does not affect the long-run behaviour but there is a transition back to balanced growth. Figure 3.4 shows GDP over time for a no-flood case and two damage scenarios. We see that the gap between cases with a flood and no flood narrows over time and is virtually gone after 20 years.

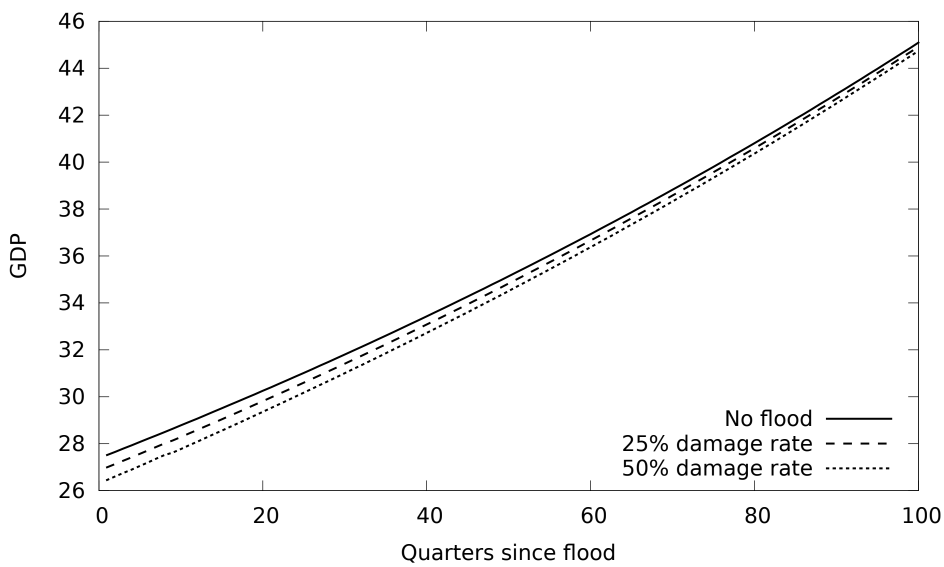

Figure 3.4: GDP timeseries for different scenarios.

In order for the capital stock to rebound so that the economy can return to the balanced growth path, a higher rate of investment is required in flood scenarios to make up for the loss of capital (this is shown in figure 3.5). In steady state, about 21% of GDP goes toward investment, which replaces depreciated capital and produces new capital needed for growth. In the 25% damage scenario, the investment percentage increases but remains below 21.5%. There is a ramp-up in the first couple of quarters as the economy adjusts to deal with the higher demand for investment.

As a result of the higher investment, the growth *rate* is higher in the flood scenarios as seen in figure 3.6. It is important to note the distinction between GDP and GDP growth. Often

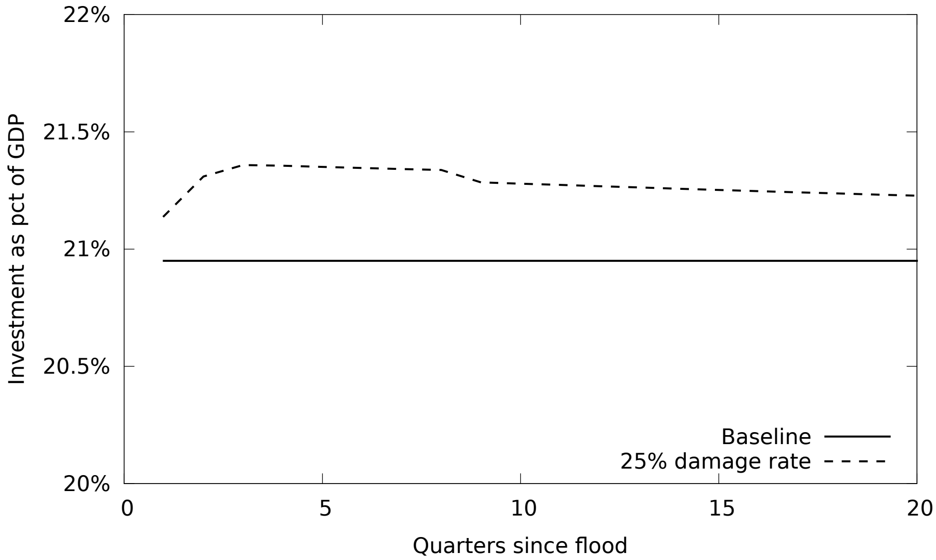

Figure 3.5: Real investment as a percentage of real GDP.

after a disaster it is noted that GDP growth increased and some argue that there are positive impacts due to reconstruction. However, this misses the fact that the GDP level is necessarily lower and consumption must have decreased ceterus paribus. Furthermore, by spending more on investment there is less available for consumption and lower consumption results in lower welfare. While certain sectors may benefit, the loss of physical capital, and possibly human capital in the case of loss of life, cannot improve the overall economy.[29]

In the first few time periods the growth rate is fairly volatile as the capital stock is rebalancing across the different sectors of the economy. A dip occurs in the 9^{th} quarter, coinciding with the ending of assistance payments. This occurs because trade must rebalance at a lower level and fewer intermediate goods are available for production.

Figure 3.7 shows the capital stock recovery for a few key sectors. We see that Construction and Manufacturing, the two most important sectors for producing investment goods, recover rapidly. Transportation and Warehousing, the most damaged sector, also recovers rapidly. Meanwhile, Finance and Real Estate actually sees a relative *decrease* in its capital stock. This occurs in the most capital-intensive industries after the flood damage because their marginal product of capital becomes smaller than other industries and thus there is little investment in capital-intensive industries. Notice that the biggest adjustment occurs in the first year after the flood and then there is a small adjustment after two years when the assistance payments end.

Next we examine the impact on trade. Figures 3.8 and 3.9 show the relative change in imports and exports, respectively. Imports of construction actually increase in the first quarter

[29]It may be possible for the disaster to improve the economy if it somehow results in eliminating inefficiencies. However, that is generally not the reason cited for a disaster having positive economic effects.

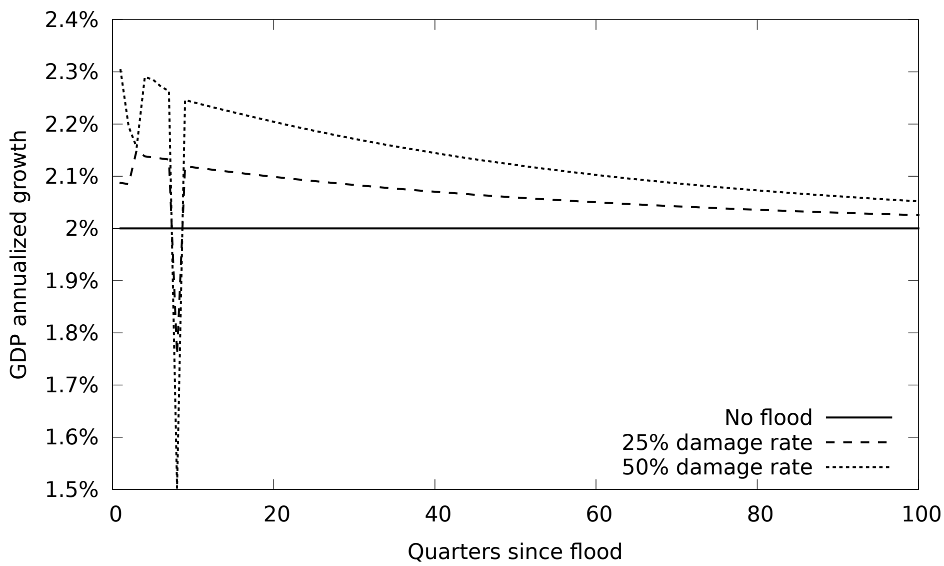

Figure 3.6: GDP growth rates for different scenarios. The dip in the 9^{th} quarter is due to assistance payments being finished.

due to the demand for investment goods. Other goods follow the pattern of domestic output (which follows the capital stock) due to prices of imports and domestically produced goods being the same. That is, there is no need to change the ratio of domestically produced to imported goods if the price ratio remains unchanged. Construction exports actually shut down completely, and as a result the domestic price is higher than the imported price. On aggregate imports must decrease if exports decrease, however the disaster assistance offsets some of that loss. After the disaster assistance payments end in the 9^{th} quarter, construction exports resume and there is a small dip in construction imports. This occurs because there is a shortage in "foreign exchange" needed to pay for imports. Nonetheless, construction exports remain low which shows the importance of construction in the recovery process.

Finally, we study the impact of the flood on government. Figure 3.10 shows the loss of (real) tax revenue in the aftermath of the flood. The initial loss is around 2% and increases over the following year before revenue begins to recover (similar to GDP). Recall that different sectors are taxed at different rates and thus the nonlinear response of the economy in the immediate aftermath of the flood results in nonlinear (and non-monotonic) tax revenues. Furthermore, tax revenues briefly flatten out in quarters 8-9 after the flood due to the expiration of assistance payments.

Figure 3.11 shows that overall the impact on government services is small, with the greatest impact being on Administration at an initial loss of less than 0.8%. The flood does not have a big impact because the capital damage is small as seen in figure 3.3. However, there is also a rapid recovery because government is very labour-intensive, not capital-intensive, and thus

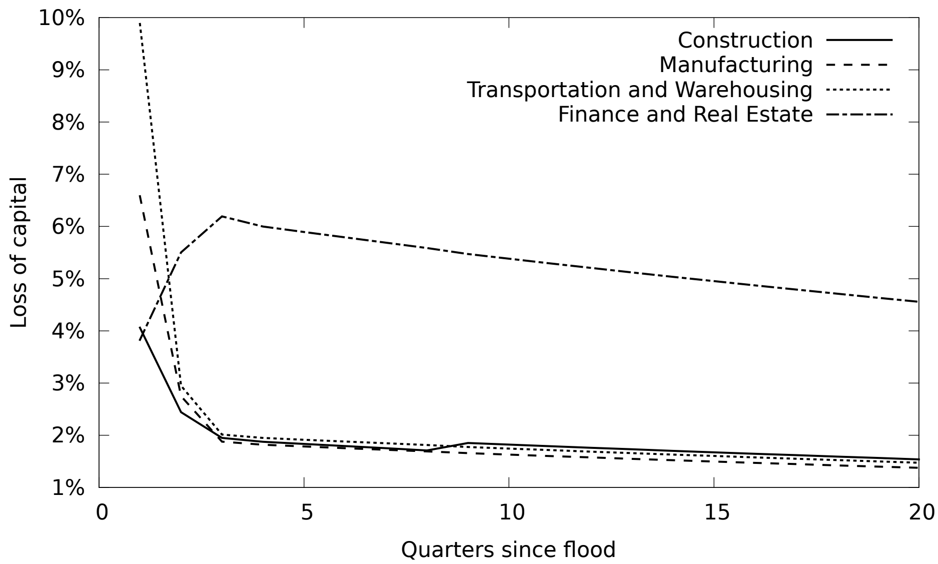

Figure 3.7: Capital stock relative to no-flood scenario for key sectors.

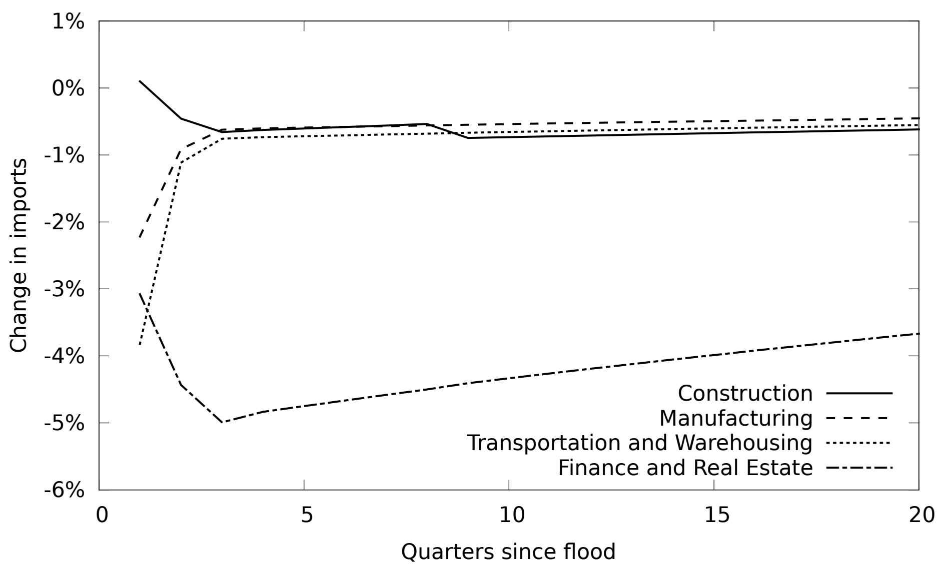

Figure 3.8: Imports relative to no-flood scenario for key sectors.

the marginal product of capital is relatively high during the recovery process.[30] The impact on government services is not as severe as that on tax revenues because the households and firms increase their direct purchase of government services.

[30]For more labour intensive industries, a small change in the capital stock has a larger impact on the marginal product of capital.

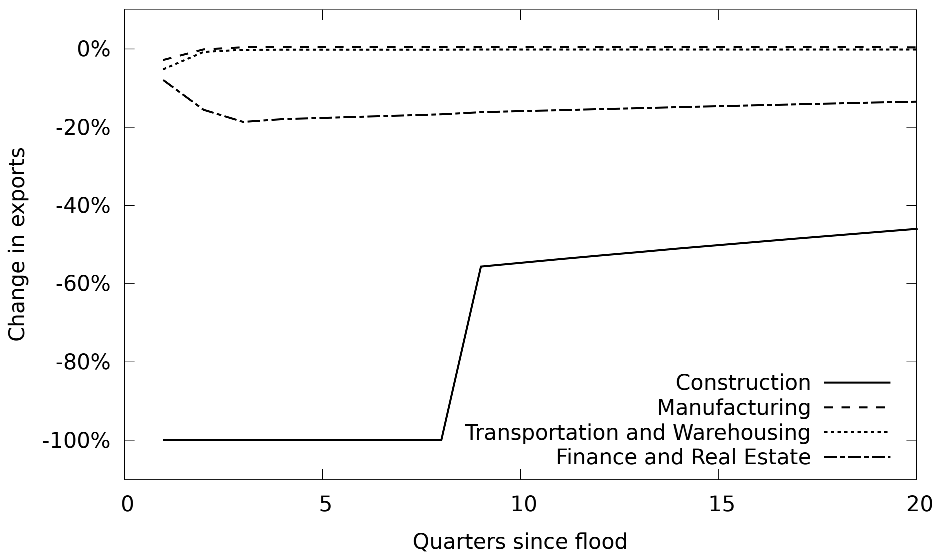

Figure 3.9: Exports relative to no-flood scenario for key sectors.

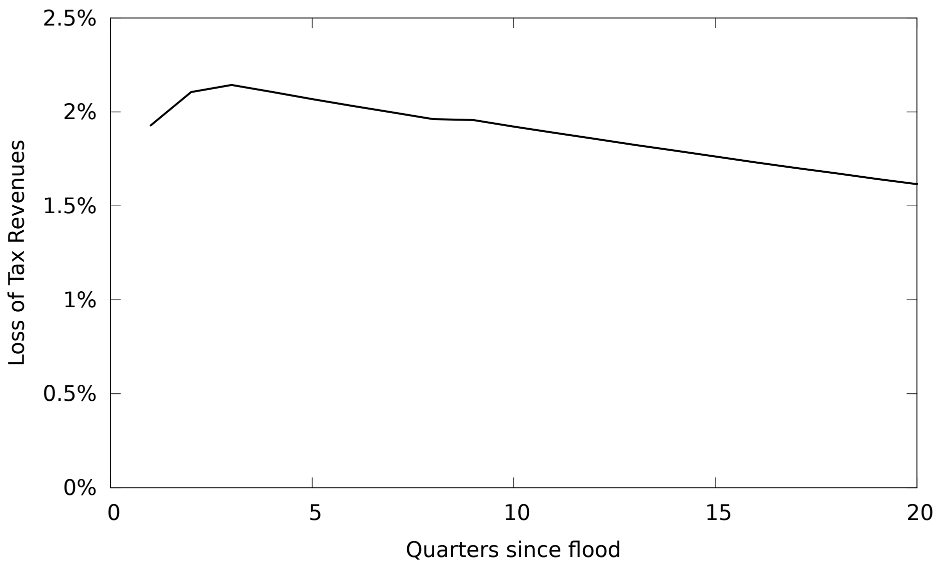

Figure 3.10: Real tax revenue relative to no-flood scenario.

3.4.2 Different damage levels

In the previous section we presented several details from the baseline simulation with a 25% damage level. Next we investigate the relationship between the economic impacts and the damage level. We are motivated by the observation of Hallegatte (2008) that indirect losses (output loss) increase exponentially with direct losses (damage). Here we consider damage rates of 5%, 10%, 15%, 20%, 25%, 35%, 50%, 75% and 100%.

Figure 3.12 shows the relationship between direct and indirect losses (output losses) where

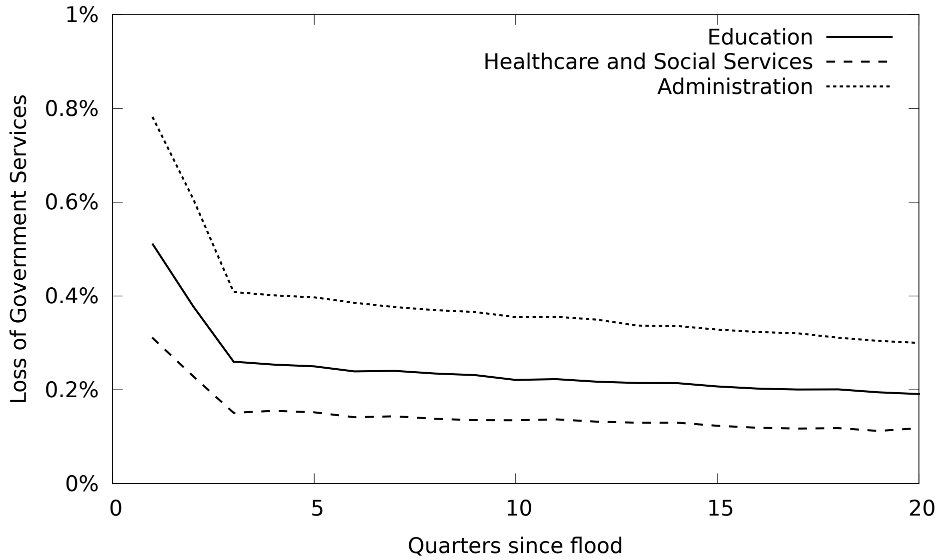

Figure 3.11: Government services relative to no-flood scenario for key sectors.

indirect losses are summed over the first 12 years and all 55 years (we consider the 12-year loss because Hallegatte's simulations reach full recovery in that timeframe).[31] The plot in figure 3.12 has the same axes as the plot found in Hallegatte's paper.

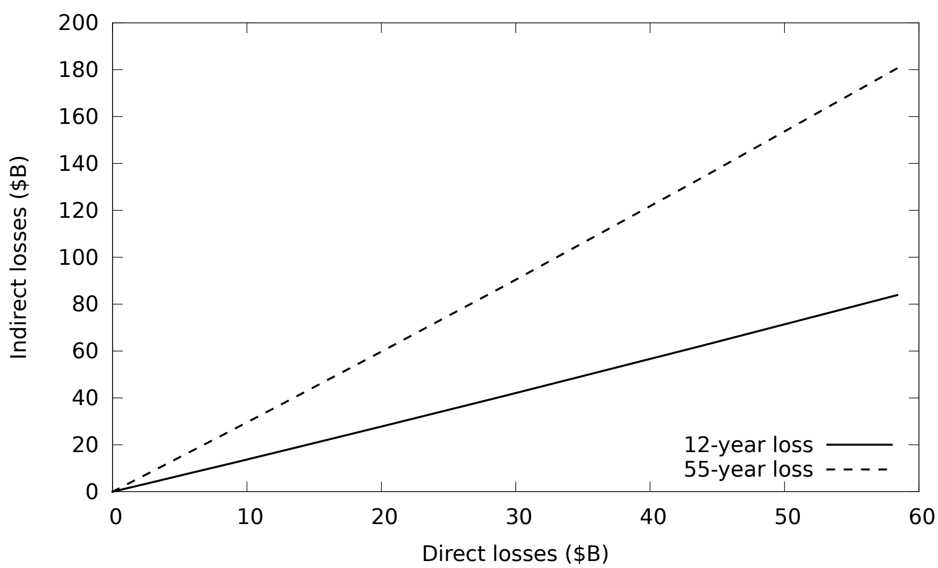

Figure 3.12: Aggregate indirect (GDP loss) vs. direct (damage) losses.

Our simulations appear to yield a linear relationship between direct and indirect losses, however there is in fact a slight exponential relationship. Table 3.4 shows the total indirect

[31]We use a discount rate of zero when summing the output losses. "Indirect loss" is the terminology used by Hallegatte for output losses.

losses (summed over years) for each damage level and the slopes between the points. The slope is in fact increasing between consecutive points which demonstrates an exponential relationship. However, the slight non-linearity found in our study is very small compared to what Hallegatte found. Furthermore, we find that whether we look at the 12-year window or the 55-year window, the indirect losses are always greater than the direct losses. Hallegatte found that direct losses dominate except at very large damage.

Table 3.4: Aggregate output losses for different damage scenarios ($B).

Damage level	12-year loss	slope	55-year loss	slope
0	0	-	0	-
3 (5%)	4	1.36	9	2.94
6 (10%)	8	1.37	17	2.95
9 (15%)	12	1.38	26	2.97
12 (20%)	16	1.39	35	2.99
15 (25%)	20	1.40	43	3.02
20 (35%)	28	1.41	61	3.03
29 (50%)	41	1.42	88	3.06
44 (75%)	62	1.46	134	3.14
58 (100%)	84	1.49	181	3.22

In Hallegatte's input-output model, there is very little flexibility to substitute. This means that for twice the damage, the construction sector's capacity is halved and as a result reconstruction takes relatively longer. In our model, prices drive an efficient allocation of investment which can mean more resources being focused on the construction sector initially. With the efficient allocation of resources and smooth recovery path, the relationship between the direct and indirect damages is much more linear.

3.4.3 Sensitivity to key assumptions

We test the impact of three key assumptions on our results:

1. Disaster assistance payments;
2. No labour mobility;
3. Key parameter choices.

We have assumed that the cost of damage will be fully covered via private insurance and public disaster assistance. However, it is possible that this disaster assistance could change in the future and not all countries have the same institutions. Therefore it is interesting to see what impact changing the level of damage compensation has on the economic cost of flooding and the recovery.

We find that the financial assistance makes very little difference in terms of GDP. Table 3.5 shows GDP levels for different years after the event in no-flood, baseline and a no-compensation scenario (all use a 25% damage rate). The assistance generates only a tiny increase in GDP initially, and after two years the gap is virtually wiped out. It is somewhat surprising that an injection of $7.3B per year for two years into the local economy has such a small effect, however the household and government do not have to spend their income during the period in which they receive it. Consequently, they choose to delay some spending in order to smooth their consumption over time.

Table 3.5: Real GDP ($B) for different scenarios in years following the flood.

Year	No flood scenario	Baseline scenario	No disaster compensation	Labour mobility
1	110.90	108.83	108.72	108.84
2	113.14	111.17	111.05	111.11
3	115.42	113.44	113.42	113.33
5	120.12	118.32	118.30	118.08
12	138.12	136.82	136.81	136.14

Next we consider the assumption of no labour mobility. We made this assumption because we are most interested in the first few years after the flood, and in the short run we expect little labour mobility across sectors. However, the fact that we necessarily restrict labour mobility in the distant future as well impacts the expectations of the agents in the model which could lead to different behaviour even in the short term. Here we allow complete labour mobility and compare the results (still using a 25% damage rate).

In table 3.5 we can see that real GDP actually *falls* after the first year relative to baseline when labour mobility is introduced. This is somewhat surprising since added flexibility should be good for the economy. However, our real GDP measure does not reflect changes in patterns of consumption driven by relative price changes. A better social measure is the welfare effect shown in figure 3.13. The increased flexibility of labour mobility allows for significant welfare gains in the early-going. In the long-run within-period welfare becomes higher than in the baseline case but this is misleading. The household is maximizing its *lifetime* utility which puts more weight on earlier periods. Thus having higher welfare in early periods is more valuable. In the case of labour mobility, the household smooths its welfare loss over all time as is expected when households have the ability to smooth.

Finally we have made parameter choices for the growth rate, depreciation and various elasticities of substitution (intertemporal, imports and domestic goods, capital and labour, con-

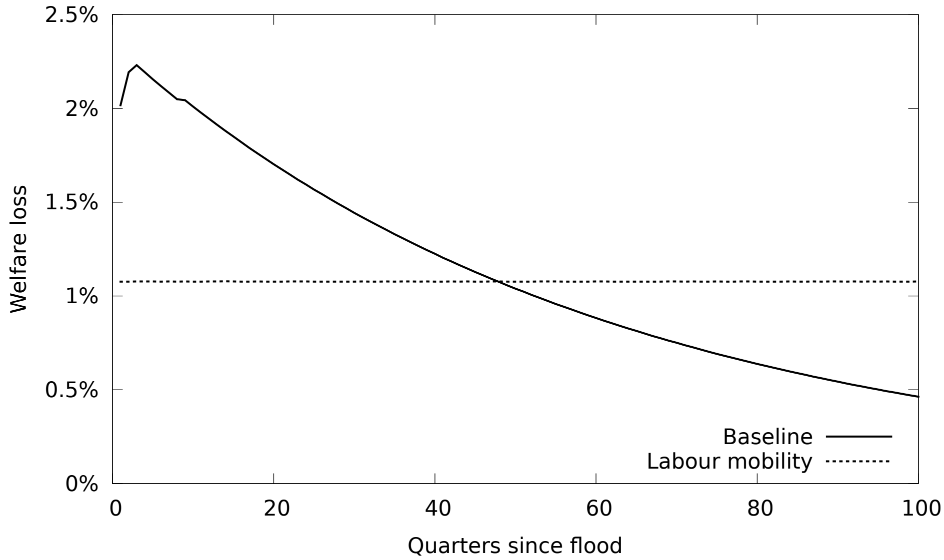

Figure 3.13: Period-by-period welfare loss compared to no flood.

sumption goods). We vary each of these parameters independently at the 25% damage level to see how our results are affected. Note that where applicable, we varied the elasticities for all goods at the same time; we did not individually test the elasticities for all 20 goods.

Table 3.6: Parameter sensitivity tests.

Parameter	Low	Base	High	GDP change at 5 years Low value	GDP change at 5 years High value
Elasticity - Armington	2	3	4	0.0%	-0.5%
Elasticity - Capital & Labour	0.5	1	1.5	0.0%	0.0%
Elasticity - Consumption Goods	0.5	1	1.5	0.0%	0.0%
Elasticity - Inter-temporal	0.5	1	1.5	-0.1%	0.0%
Growth rate	-	2%	5%	-1.31%	
Depreciation	-	5%	10%	-1.16%	

We initially selected an Armington elasticity of 3 for our simulations because it's a common choice in the literature, although some studies choose higher values like 4. In our sensitivity tests, we found that varying this elasticity between 2 and 4 had virtually no impact on the results (table 3.6 shows the change in GDP at 5 years for the high and low parameter values). For the elasticity of substitution between capital and labour, it is common in the literature to choose a value of 1 which reflects the stylized fact that the capital and labour income shares are roughly constant. As we varied this parameter between 0.5 and 1.5, it also had no meaningful impact on GDP and welfare levels (less than 0.1% change in GDP and welfare through time). For the elasticity of substitution between consumption goods, we initially chose a value of 1 which is common in CGE studies. We found that varying this parameter had virtually no impact as well. Finally, even varying the inter-temporal elasticity had little effect on GDP. It had more of an effect on welfare than the other elasticities, but that difference remained below 1%.

Compared to the elasticities, varying the growth and depreciation rates had larger impacts. In order run these sensitivity tests, we had to recalibrate the model because these parameters affect the determination of the BGP interest rate. In the base case, GDP is 1.50% behind the no-flood scenario at the 5-year mark. When the steady state growth rate is increased to 5%, GDP only lags by 1.31% at the 5-year mark (going from 137.66 in the no-flood case to 135.86 in the 25% damage scenario). The loss from the flood drops because the economy is more productive and thus can recover more rapidly. When depreciation is increased from 5% to 10%, the GDP loss at the 5-year mark decreases to 1.16%. This occurs because in the calibration, r increases with δ, and K_0 decreases as r increases. Thus less total rebuilding is required to return to the BGP. While the growth rate and depreciation parameter choices affect the results, the impact is relatively minor in magnitude. The findings in the paper appear to be very robust to parameter changes.

3.5 Conclusion

This paper has developed a novel dynamic CGE framework for modelling the economic impacts of flooding and the subsequent recovery. Damages in our framework are based on specific flood scenarios which can respond to various adaptation measures, and affect every economic sector. The model incorporates the recovery mechanism from the input-output model of Hallegatte (2008): investment using local production and imports rebuilds the capital stock. In our model, investment and resource allocation decisions are endogenized and we solve for the efficient recovery path.

We calibrate the model to data for Metro Vancouver, which is considered to be one of the most vulnerable cities in the world with respect to possible flood damage. In our baseline scenario, flooding of the lower Fraser Valley causes total capital damage in Metro Vancouver of \$14.6 billion. Transportation and Warehousing are the most severely affected industries, followed by Manufacturing and Wholesale Trade. The construction sector plays a very important role in the recovery process. Capital intensive industries, even those not directly affected by the flood, suffer from a higher cost of capital goods during recovery.

We find that the GDP loss relative to a scenario with no flood is 1.9% (\$2.07B) in the first year after the flood, 1.7% (\$1.97B) in the second year, 1.5% (\$1.70B) in the fifth year and 1.1% (\$1.42B) in the twentieth year. We have also found that the losses tend to rise at a mildly increasing rate with the size of aggregate damage. In total, in our base scenario, output loss over our full 55 year horizon is $43 billion, which is close to being three times as great as the capital damage of $14.6 billion caused by the flood. While Vancouver residents benefit from the modelled disaster assistance, we find that the latter has relatively little impact on the time path of output. That is because we have assumed well-functioning capital markets, so that when there is less assistance there is simply more borrowing and the rebuilding of capital remains efficient. Results are also relatively insensitive to allowing free labour mobility and to changes in most of the freely-chosen parameters of the model. Results are more sensitive to the assumed depreciation rates and growth rate but are relatively robust even in the face of those changes.

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Chapter 4

Do developing countries face a higher cost of reducing carbon emissions?

Developing countries are among the largest CO_2 emitters in the world. In 2010, the top emitters were China (8.3 Gt), the U.S. (5.4 Gt), the E.U. (3.7 Gt), India (2.0 Gt), Russia (1.7 Gt) and Japan (1.2 Gt) (World Bank, n.d.). Historically, growth drives energy demand, thus fast-growing developing countries are expected to contribute the majority of emissions going forward. As a result, any successful plan to limit global emission growth must include developing countries (e.g., see Stern, 2007).

Although developing country action is required to stabilize emissions, some argue that developing countries cannot make the same types of carbon reduction commitments as developed countries without seriously harming their economic development.[1] The basis for this argument is that the energy mix for developing countries tends to be very carbon-intensive (i.e. heavy coal use). This is compounded by higher energy intensities[2] in developing countries compared to developed countries (see table 4.3).[3] In order to lower emissions, carbon-intensive energy consumption must be reduced, but "clean" energy is typically more expensive. The economic impact of reducing carbon emissions will depend on the ability to implement non-fossil fuel energy sources and reducing energy consumption overall.

Although there are large differences in the energy mix and intensity across countries, it is unclear whether these differences imply *quantitatively important* differences in the cost of lowering carbon emissions.[4] If the cost is small, then developing economies should be able

[1]Even for developed countries to take action alone could have significant negative impacts on developing economies (Babiker et al., 2000).

[2]Energy consumption per unit of GDP.

[3]Section 4.1 gives a detailed overview of historical and cross-country energy use and fuel mix trends.

[4]There are obvious economic benefits to avoiding climate change. However, the benefits to climate avoidance accrue to the entire planet. In this paper I employ a single-country model, therefore the added complexity of

to reduce emissions without incentives from developing countries. If the cost is high, then transfers from developed to developing nations will be needed to stabilize global emissions.[5]

This paper quantitatively compares the cross-country economic impacts of lowering carbon emissions, highlighting differences resulting from energy efficiency and fuel mix variations. I perform this exercise by simulating an energy-economy model for a selection of developed and developing economies under different carbon emission reduction policies. The variation in the macro economies and energy sectors across countries is accounted for through the calibration of the model parameters to the data. To quantitatively assess how cross-country differences in energy sector characteristics matter, I compare my simulation results across countries for the carbon taxes required to achieve the same percentage decline in emissions in each country.

Since answering this question requires looking at policy impacts over the long run (more than 30 years), I employ the neoclassical growth model and augment it by adding an energy sector. The neoclassical growth model is appropriate for a problem with a long time horizon because it smooths over short run cycles and has a stable long run solution. The explicit energy sector allows for studying the impact of a carbon tax on energy consumption and output. In the model, a final good producing firm uses capital, energy services and labour as inputs. Energy services is a composite of "clean" and "dirty" energies, which are aggregated using a CES function. The energy sectors use only capital as an input. CO_2 emissions are a product of the dirty energy sector. A representative household maximizes utility by choosing consumption and investment.

A tax on emissions drives substitution along two key margins. First, there is substitution away from costlier dirty energy toward clean energy. Second, since the overall cost of energy is higher, there is substitution toward capital and labour from energy. The higher price of energy lowers GDP because it is more expensive to produce goods. The impact of the energy price increase on GDP will depend on the extent of the economy's energy dependence (relative to capital and labour) and the carbon intensity of the energy sector.[6]

In order to simulate the model and quantify the economic impacts of carbon policy, I calibrate the model for a six developing and six developed countries. The countries vary in their parameter values; of particular importance to this study is that developing countries tend to have higher energy intensities and dirtier fuel mixes. The parameters are determined by matching key moments in the data for each country, like the energy share, the fuel mix (i.e. clean vs. dirty energy use), the capital share, the growth rate and the rate of capital formation (savings

climate-feedbacks on the economy is not insightful.

[5]As of 2011, approximately $32US billion in total had been promised to developing countries for climate change mitigation and adaptation (Climate Funds Update, n.d.).

[6]It will also depend on adjustment costs associated with changes in energy consumption and fuel mixes. However, that is not the focus of this paper.

rate).

I simulate the dynamic behaviour of all 12 economies. The simulations are run under four scenarios for each country: baseline (no emissions reduction); and 10%, 25% and 50% emissions reductions vs. baseline. The emissions reductions scenarios are achieved by tuning a carbon tax appropriately. The carbon tax results in a reduction in energy consumption via the mechanisms described above; the tax raises the price of dirty energy driving the substitution of clean energy for dirty energy and the substitution of value added for energy services. The drop in energy consumption lowers output. I compare the economic impacts of the carbon tax policy, most importantly the change in GDP, across countries for each of the scenarios.

The results of the simulations show that the energy economies of developing countries (especially the two largest, India and China) make it much more costly for them to reduce emissions.[7] This is true of the GDP level and the growth rate during the transition to the balanced growth path. For example, for a 50% reduction in emissions in China (a relatively coal-dependent country), the output level drops by 6.7% per year. India's long run output loss is 3.8% per year. For the same 50% reduction in emissions, the output level drops by less than 1% in all developed countries, except Canada whose output falls by 1.2%. The *growth rate* reductions along the transition path also differ. Again for a 50% reduction in emissions, China's growth rate drops from 7% to 6.5% at the beginning of the transition path, whereas the decline for France is from 1.5% to 1.44% (similar for other developed countries). Furthermore, it takes longer for China to re-converge toward the balanced growth rate. These significant differences imply that developing countries, particularly those with heavy coal use, will require transfers from rich countries to offset materially larger economic losses from implementing carbon policy.

Most studies of the cost of climate policy have used multi-sector models but have focused on a single country.[8] This paper contributes to the literature by quantifying how the cost of reducing emissions varies *across countries* due to the differing structure of energy sectors. I use the same framework for all countries which allows me to compare the impacts of equivalent policies in a consistent fashion.

Many of the single-country studies have more sectoral detail than the model used in this paper, yet the findings herein are consistent with those generated by more sectorally detailed models. Zhang (1998a,b, 2000) investigated scenarios where Chinese emissions are cut by 20% and 30% in 2010 compared to a baseline scenario beginning in 1990 (using a carbon tax). This resulted in 1.5% and 2.8% decreases in 2010 GNP, respectively; I find a 2.84% long run

[7]Amongst developing countries, Brazil and Mexico experience much smaller losses due to their less energy and coal intensive economies.

[8]They also omit climate feedbacks on the economy, like the model in this paper. This is sensible for reasons stated above.

loss in GDP for a 25% emissions reduction. Wang et al. (2009) modelled the Chinese economy with endogenous technological change. They found that the GDP cost of reducing emissions is 6.19% for a 50% reduction in 2050, but a subsidy for research and development lowers the loss to 3.87%.

In a study for India, Fisher-Vanden et al. (1997) found that to stabilize emissions at 1990 levels would result in a 6% loss in GDP by 2030, whereas stabilizing at three times 1990 levels would result in virtually no loss. Tripling emissions over 40 years corresponds to a 2.8% annual increase. Since that level of emissions increase results in no losses, we can consider it as a baseline scenario. In my simulations I used a 7% growth rate for India, however I used a 3% growth rate for South Africa which has a similar energy sector to India (although invests much less). I find a 3.44% loss of GDP for a 50% emissions reduction versus the baseline scenario for South Africa. If losses scaled linearly (I actually find they scale exponentially), a 67% emissions reduction (corresponding to stabilizing emissions versus a tripling) would result in a 4.59% loss of GDP. My model would actually yield a greater loss due to the exponential response of losses to emissions reductions. Thus my results correspond well to Fisher-Vanden's 6% GDP loss, despite modelling differences and the fact that the paper was published in 1997 and hence used much older data.

Using a multi-region model (not multi-*country*), Whalley and Wigle (1991) found that "developing and planned" economies experience a loss of 7% of GDP for a 50% reduction in emissions for the period of 1990-2030 using national carbon taxes; losses were between 1% and 4% for OECD countries. The losses I find for a 50% emissions reduction are smaller but reasonably close; China loses 6.7% of GDP and developed economies lose around 1% in the long run. These results are similar despite model differences (sectoral detail, trade) and the fact that my study uses much more recent data which is not aggregated across countries.

The majority of the CGE models in the literature, including all those cited here, are static or use exogenous investment; investment in the model considered here is endogenous. Endogenous investment allows for more rapid substitution away from costly energy toward capital as the household can save a greater share of income in response the higher demand for investment (only the transition would be affected, not the long run). Therefore, the (transition) losses in my model are smaller than under exogenous investment. However, these differences are probably not large - testing performed in a previous version of the paper showed very small differences between exogenous and endogenous investment simulations (Gertz, 2011).

The paper is organized as follows. In section 4.1, I discuss the history of energy intensity and energy mix in developed countries and how that compares with developing countries of today. Section 4.2 describes the model and data and section 4.3 presents the results. A discussion of the results is offered in section 4.4.

4.1 Development and Energy

This section summarizes important empirical cross country regularities on the two key factors that determine an economys carbon intensity: energy efficiency and fuel mix. These factors are at the heart of the argument that developing economies cannot afford to make large emissions reductions because it is too costly. Energy intensity and fuel mix are built into the model presented in section 4.2 and drive the quantitative cross-country differences in the cost of reducing carbon emissions presented in section 4.3.

That data shows that developing countries are less energy efficient (see table 4.3). This is due to employing less advanced technology and having lower overall productivity. Not only do developing countries have higher energy intensities today, but this section shows that energy intensity has been persistently declining in the U.S. and overall energy consumption has generally plateaued in developed countries while it increases rapidly in developing countries. Fuel mix differences can be more complicated, but since fossil fuel energy is cheaper and developing countries are less energy efficient, developing countries tend to have dirtier fuel mixes. However, geography (and climate) and government policy also affect energy consumption patterns, particularly the fuel mix. Consequently, while the dirtiest energy sectors belong to developing economies, other developing economies have relatively clean energy sectors.

4.1.1 U.S. Historical Energy Patterns

Developing countries today emit more carbon per unit of GDP than developed countries. However, their emissions intensities can be expected to improve as part of the development process, as the energy intensity in most developed countries has declined over the past 60 years (for the U.S., see figure 4.1). The CO_2 intensity follows a similar pattern to the energy intensity, as carbon emissions have been largely driven by energy usage. However, there is some variation in the two intensity measures and this is a result of the energy mix changing. This is particular evident during the 1950s.

Figure 4.2 shows the changing energy mix for the U.S., as the dominant energy source went from wood to coal to oil. Petroleum and natural gas surpassed coal as an energy source around 1950, driving a decrease in CO_2 intensity as oil and gas are less emissions intensive than coal. These changes largely came about due to technological advances and changes in the industrial makeup of the country; demand for electricity helped to drive an increase in the demand for coal, the automobile resulted in a surging demand for oil and advanced metallurgy paved the way for widespread natural gas distribution.[9] However, price shocks also impacted the fuel

[9] Nuclear power was a direct result of a technological advance.

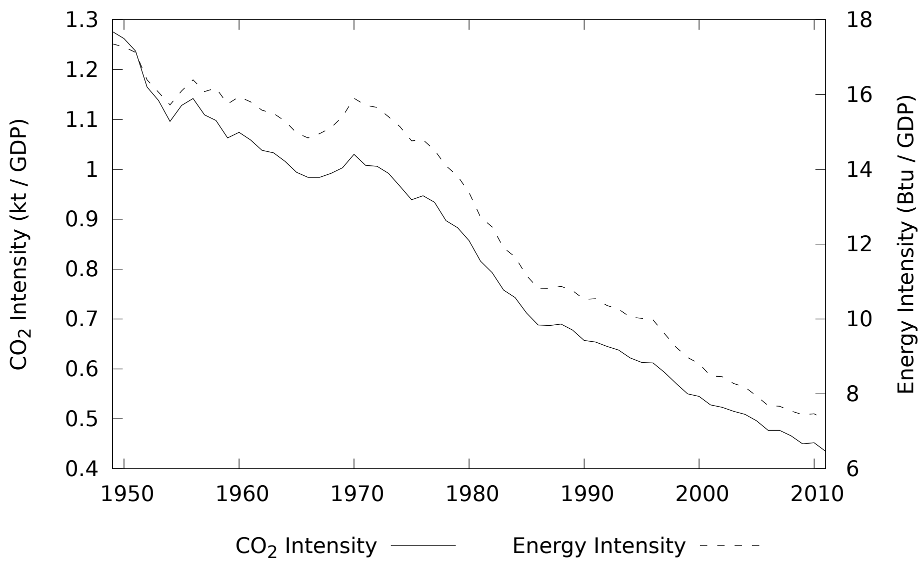


Figure 4.1: Historical U.S. CO_2 and energy intensities. GDP in real 2005 USD. Source: Energy Information Administration (2010), Bureau of Economic Analysis (n.d.).

mix as the OPEC oil embargo during the 1970s reduced oil consumption and increased coal consumption.

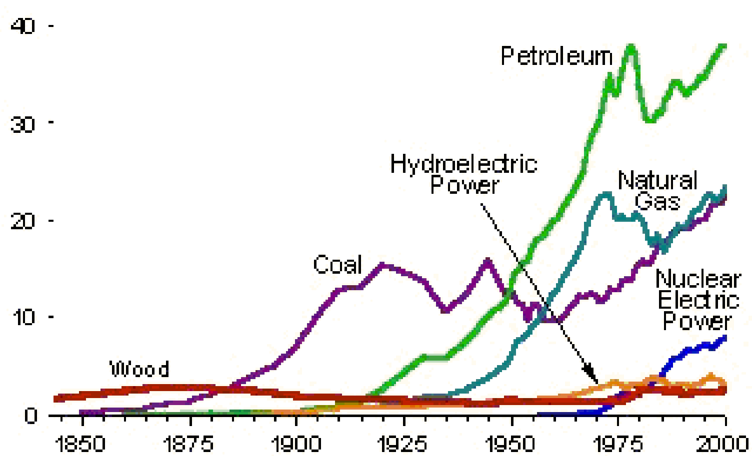


Figure 4.2: Historical U.S. energy consumption by fuel type. Source: Energy Information Administration (2010).

The consumption of different fuel types by sector in the U.S. is shown in figure 4.3 for 1974 and 2008. The predominant changes over the past 35 years are a growth of the transportation sector and consequent increase in oil consumption, and increased in electricity consumption by non-industry (residential, services, etc.). Industrial energy use has actually declined over that period.

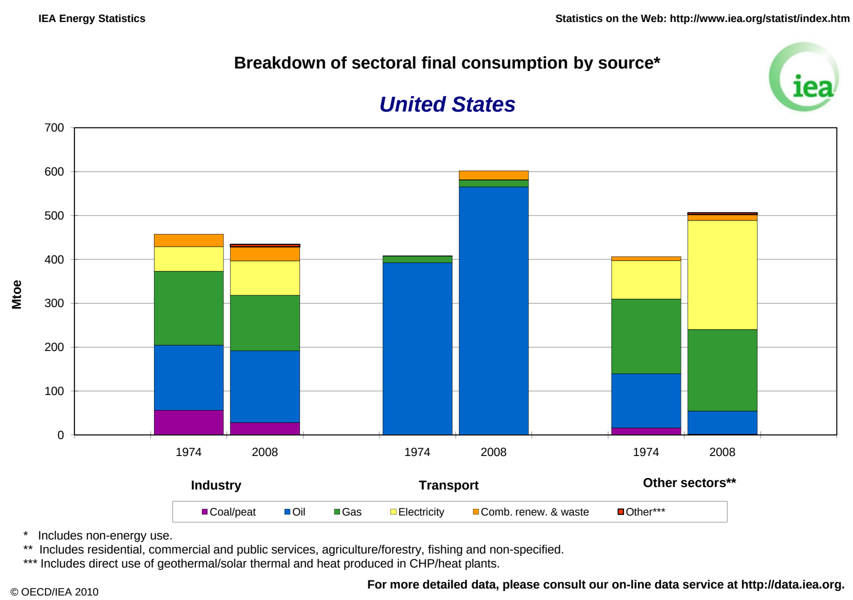


Figure 4.3

4.1.2 Cross-Country Energy Use Comparison

Fuel mixes vary considerably across all countries, however overall consumption tends to be increasing much more rapidly in developing countries. The fuel mix tends to largely be determined by natural endowments of resources. Countries with large endowments of coal include China, South Africa, the U.S. and Germany; countries with large endowments of oil/natural gas include Russia and the U.K. Beyond the natural endowments, government choices seem to play a larger role for developed countries, such as whether to adopt nuclear power or renewable energy (both tend to be more expensive than fossil fuel power).

Figure 4.4 shows the total consumption and fuel mix in electricity generation for a set of developing countries (the majority of CO_2 is emitted from generating electricity). Total consumption of electricity has levelled off or even gone into decline in developed countries. In terms of fuel mix, coal accounts for about half of both the U.S. and Germany's electricity distribution, but is used much less in the other countries shown here. However, Germany uses relatively more nuclear power and has larger nascent renewable energy sector.[10] Meanwhile the French energy sector is dominated by nuclear power and the UK has considerable natural gas generated electricity from the North Sea oil fields, growing significantly since 1990 (but recently this source has been in decline). The stark differences between the UK, Germany and France show that even nearby countries with relatively similar economies can have very

[10]This is largely a result of government policy.

different energy sectors. Canada obtains the majority of its electricity from hydro,[11] another case of a natural endowment playing a key role. Japan has a balanced mix of fuels in electricity generation, although nuclear power was shut down after the Fukushima disaster in March, 2011.

The total consumption and fuel mix in electricity generation for a set of developing countries is shown in figure 4.5. Apart from Russia, the developing economies show sustained growth in electricity generation. In terms of the fuel mix, there is variation across developing countries (as there was across developed countries). However, the energy profiles of China, India and South Africa are very similar in their dependence on coal. China and India are by far the two largest emitters among developing countries. Both predominantly use coal in electricity generation, along with some hydro power, and their electricity consumption is increasing rapidly. India also uses a small amount of natural gas. South Africa also uses coal almost exclusively to generate electricity, with a small amount of nuclear power. Russia has a completely different energy profile as it saw a sharp decline in electricity consumption following the break-up of the Soviet Union, although electricity has increased slowly since the mid-90s. The largest fuel source in Russia is natural gas. Brazil is unique in that almost all electricity generation is from hydro power, although other sources have come online in the past decade. Mexico has seen a growth in natural gas electricity generation since the late 90s associated with new oil fields.

The energy data presented here motivates this paper. First, while electricity consumption has stabilized in developed countries, it is rising rapidly in developing countries. This implies that developing countries are critical to climate change mitigation since they will be the major source of future emissions assuming current trends hold. Second, more developed economies tend to be more energy efficient. Third, fuel mixes vary considerably across countries but developing countries tend to have more carbon intensive fuel mixes. These energy facts are incorporated into the model presented in the next section, which allows me to quantitatively assess their importance to the cost of reducing emissions. Consequently, I can compare the cost of climate policy across countries.

4.2 The Model

The model extends the standard neoclassical growth model by adding energy as an input to production, in addition to capital and labour. Energy is comprised of "clean" and "dirty" components, where the dirty energy gives off carbon emissions. The household maximizes lifetime

[11] While Canada has a relatively clean electricity sector, it does generate considerable carbon emissions from the production of oil.

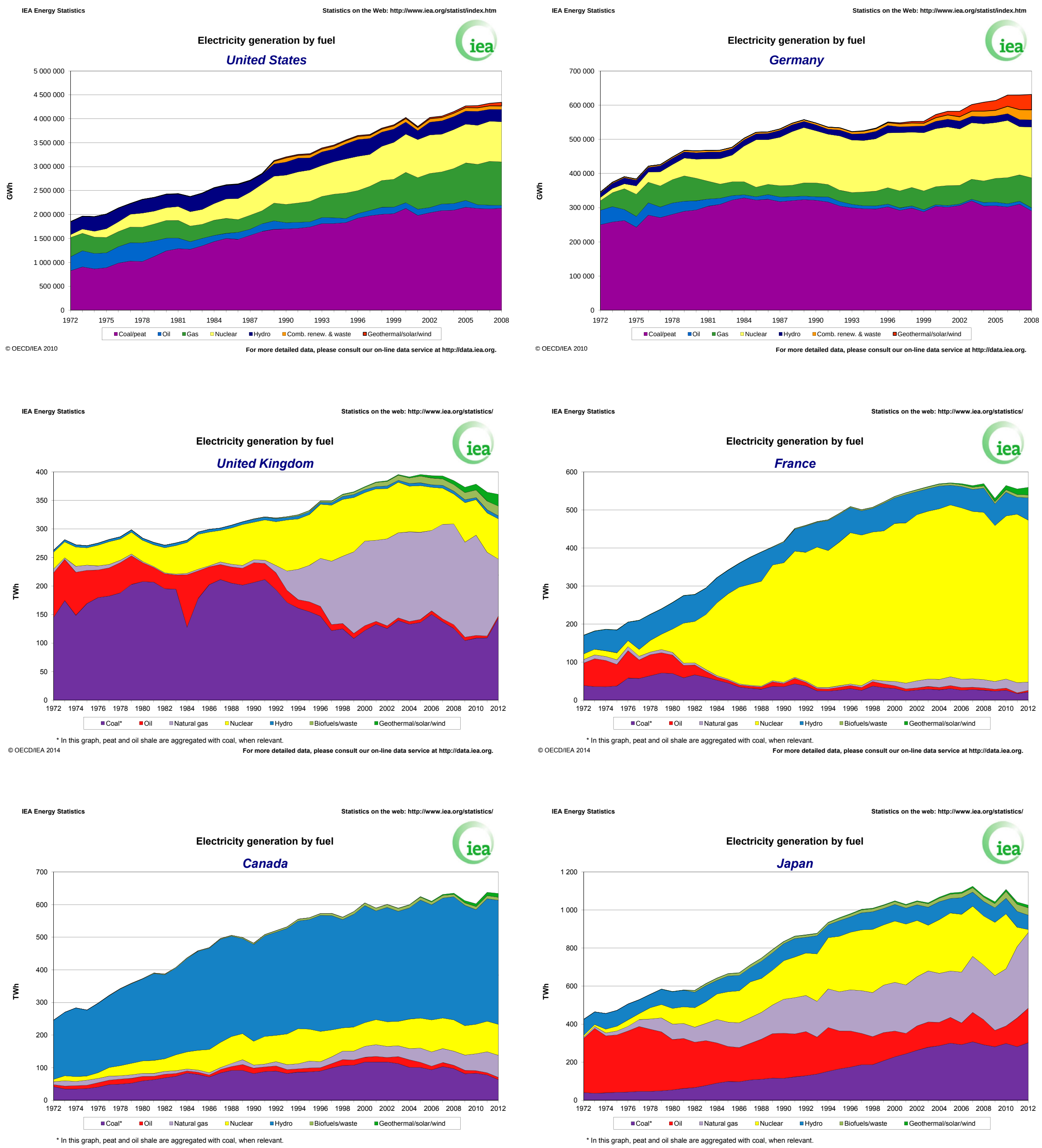


Figure 4.4: Fuel mix of electricity generation for several developed countries. Note that there is some inconsistency in the colours across figures.

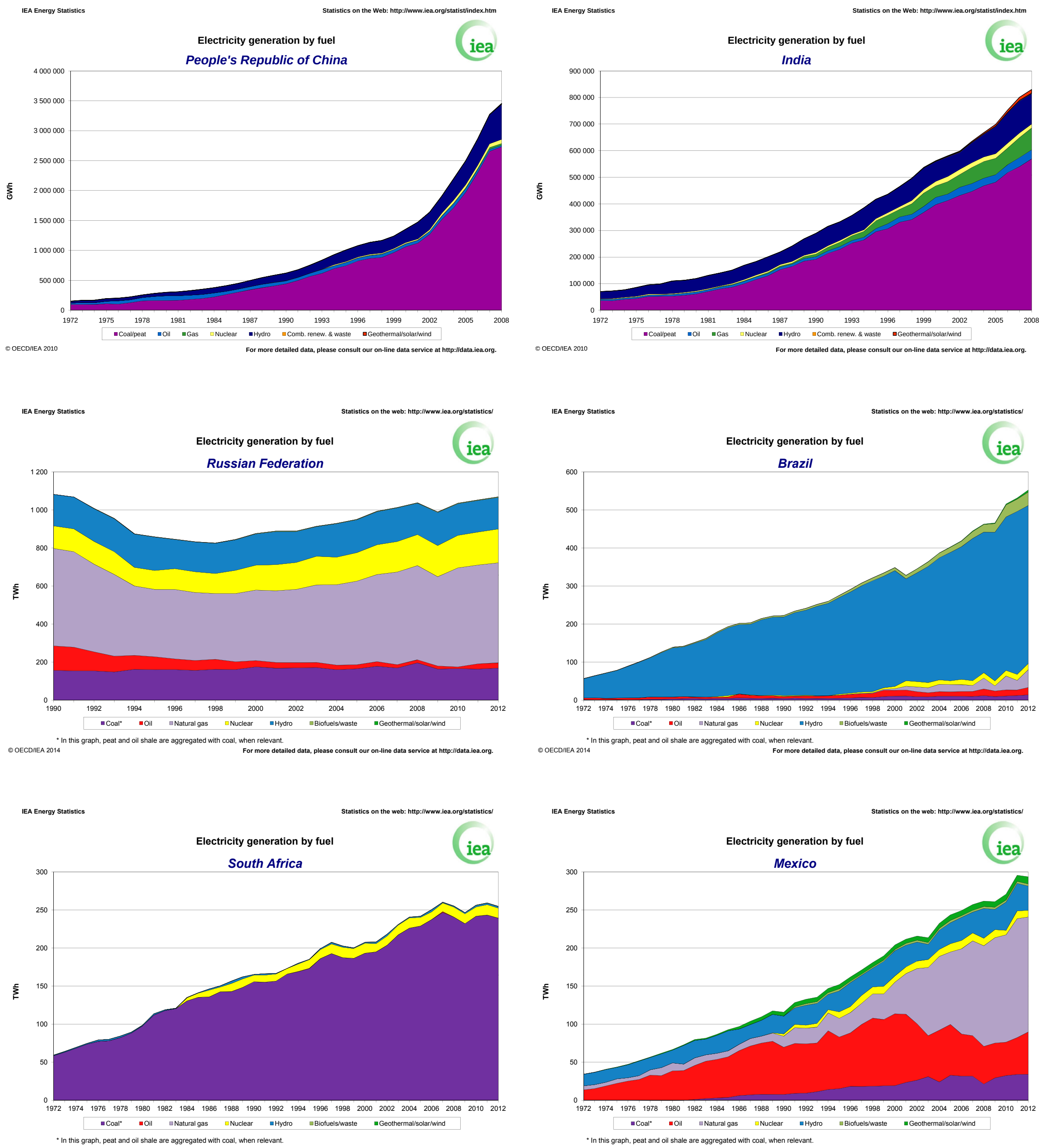


Figure 4.5: Fuel mix of electricity generation for several developing countries. Note that there is some inconsistency in the colours across figures.

utility by choosing consumption and investment each period.

Since clean energy is more costly to produce than fossil fuel energy, effective policy to reduce emissions must either increase the price of dirty energy or reduce the price of clean energy. The former can be achieved through a carbon tax or by putting a cap on emissions (e.g. cap and trade).[12] The latter can be achieved by subsidizing clean energy, however for this option to be efficient policy-makers must properly determine the appropriate level of subsidy (for each type of clean energy) to achieve the desired reduction in emissions. Due to the difficulty in choosing and maintaining an efficient subsidy policy, a tax or cap scheme is generally considered more effective. Therefore, a carbon tax is used here to lower emissions.

4.2.1 Household

A single representative household has log utility over consumption with discount factor β.[13] That is, for consumption stream $\{C_t\}_{t=0}^{\infty}$, utility is given by:

$$U(\{C_t\}_{t=0}^{\infty}) = \sum_t \beta^t \log C_t. \tag{4.1}$$

The household chooses consumption and investment for each period to maximize lifetime utility subject to its budget constraint. The household owns capital which it supplies to the market, along with labour. Without loss of generality, I set the labour supply to constant.

4.2.2 Production

The final good is produced by a profit-maximizing firm by using capital, K_t^f, labour, L_t, and energy services, E_t as inputs. Capital and labour are supplied from the household at prices r_t and w_t, respectively. Energy services are purchased from a "utility company" at price p_t. The production function is given by:

$$Y_t \leq A_t^f (K_t^f)^{\alpha_k} E_t^{\alpha_e} L_t^{1-\alpha_k-\alpha_e}. \tag{4.2}$$

Here, Y is output of the final good and A^f is total factor productivity. The price of the final good is made numeraire.

In order to account for differences in energy sectors across countries, the utility company uses dirty energy and clean energy as inputs to create energy services. It maximizes profits

[12]Note that the cap and trade scheme imposes a price/rate on emissions. If carbon were taxed at that rate it would result in the same marginal cost of emitting. Thus the two schemes are equivalent and the optimal policy depends on the cost of implementation.

[13]Leisure is not in the utility function, hence labour is supplied inelastically.

using the following technology:

$$E_t \leq A^e(a(E_t^d)^\rho + (1-a)(E_t^c)^\rho)^{1/\rho}. \tag{4.3}$$

In the above CES aggregator, $s = \frac{1}{1-\rho}$ is the elasticity of substitution between clean and dirty energy. Dirty energy and clean energy are produced using only capital as an input, so this gives $E_t^d = A^d K_t^d$ and $E_t^c = A^c K_t^c$. Assuming the energy producers make zero profits, π^d and π^c, the following is obtained:[14]

$$\pi^d = p^d E^d - r^d K^d - \tau M, \quad \pi^c = p^c E^c - r^c K^c.$$

The $M = \phi E^d$ term is CO_2 emissions[15], where ϕ is a country-specific parameter that gives emissions per unit of dirty energy consumed. The parameter τ is the carbon tax per unit of emissions. The energy firms are assumed to make zero profits, so that prices can be solved in terms of r and parameters.

The market clearing conditions are given by

$$Y_t = C_t + k_{t+1} - (1-\delta)k_t \tag{4.4}$$

$$k_t = K_t^f + K_t^d + K_t^c \tag{4.5}$$

$$l_t = L_t \tag{4.6}$$

where δ is depreciation and k_t and l_t are the capital and labour supplied by the household.

4.2.3 Model solution

An equilibrium given an initial capital stock, k_0, is defined as a sequence of prices $\{r_t, r_t^d, r_t^c, w_t, p_t, p_t^d, p_t^c\}_{t=0}^\infty$ and quantities $\{Y_t, C_t, K_{t+1}^f, K_{t+1}^d, K_{t+1}^c, L_t, E_t, E_t^d, E_t^c\}_{t=0}^\infty$ such that given those prices, the quantities solve the household, firm and utility company problems; and the markets for goods, capital and labour clear.

A balanced growth path is an equilibrium such that the rate of return on capital is constant, $r_t = r$, and all quantities, except labour which is fixed, grow at the same constant rate, g.[16] Given k_0 and the parameters of the model (including the carbon tax rate), there is a unique solution to the model which converges to the balanced growth path as $t \to \infty$.

[14] r_t^d and r_t^c, the prices of capital for the dirty and clean energy producers, must equal r_t by the household problem.

[15] I abstract from other sources of greenhouse gases such as methane since they are not a large fraction of total emissions, and they are largely a product of the agricultural sector.

[16] Along the balanced growth path wages grow at rate g because labour is fixed, and the energy prices are constant.

4.2.4 Model Mechanics

The purpose of the model is to enable the study of how taxing the energy sector affects output. Here, I explain the mechanisms through which the carbon tax impacts output in the model (for an overview see table 4.1). This provides intuition for the results of the numerical simulations in section 4.3 where carbon is taxed in different countries and the economic impacts are compared.

Adding a carbon tax raises the price of dirty energy, decreasing demand for dirty energy. If the price of clean energy was fixed, then demand for clean energy would necessarily increase because its price relative to dirty energy has decreased. However, the increased demand for clean energy pushes up its own price. In equilibrium, clean energy consumption can go up or down depending on model parameters. However, an increase in the carbon tax always leads to an increase in the price of clean and dirty energy. Therefore, the cost of producing energy services increases since it relies on clean and dirty energy as inputs. Consequently, the "utility company" must raise the price of energy services to offset the higher costs; as a result demand decreases.

Table 4.1: Impact of carbon tax

	E_d	E_c	E	K	L	Y
Price	↑	↑	↑	↑	↑	-
Demand	↓	?	↓	?	-	↓

If the price of value added (capital and labour composite) was fixed then demand for it would necessarily increase, but the increased demand drives up the price of value added (the quantity of value added used can go up or down in the long run equilibrium via investment decisions, depending on model parameters, although labour is fixed). Furthermore, the increased cost of capital further increases the cost of producing energy. Since the prices of value added and energy services have increased, the cost of producing final output increases. Consequently, the price of the final good must increase which reduces the demand for it (lowering GDP).

The level of the GDP loss depends on a few key model parameters:

1. Elasticity of substitution between clean and dirty energies (s): A larger value means that clean energy can be substituted for dirty energy more easily, lowering the overall cost of the tax.

2. The dirty energy share parameter (a): This determines the initial relative quantities of clean and dirty energy in the economy, hence also determining the relative prices. If

the price of clean energy is very high relative to dirty energy to begin with, driving substitution toward clean energy is more costly.

3. The energy services share parameter (α_e): This reflects an economy's initial energy intensity and hence the price of energy services relative to value added. If the price of value added is very high relative to energy services to begin with, driving substitution toward value added is more costly.

The elasticity of substitution between value added and energy services is implicitly assumed to be 1 due to the Cobb-Douglas production function, but the results would also be impacted by a change in this value. In the numerical simulations, s will be constant across countries but a and α_e will vary. The carbon tax rate is also a key parameter in the model that affects the level of GDP. In the numerical exercises this parameter will be tuned to achieve a targeted reduction in emissions common to all countries.

4.2.5 Data and Calibration

In order to simulate the model to compare the cost of lowering emissions across countries, the model must be calibrated. To do so I match moments in the data for each country for a given year, like capital and energy shares. In many cases the moments are calculated from underlying data. Specific details of the calibration exercise are provided below.

I calibrate the model to the year 2012 for six developing countries and six developed countries. The developing countries are Brazil, China, India, Mexico, Russia and South Africa. The developed countries are Canada, France, Germany, Japan, the U.K. and the U.S..

The model is calibrated by solving the equations in the model for the unknown parameters in terms of output, final good capital, capital of the dirty and clean energy sectors, total energy consumption, energy consumption from the dirty and clean energy sectors and the long-run growth rate. Data on carbon emissions are used to compute a conversion factor from dirty energy to emissions. Population data is used to convert quantities into per capita terms. I obtain values for these quantities and take a stand on depreciation and the discount rate.

I solve for the model equilibrium assuming that the respective economies are following the balanced growth path in the base year (2012). I assume values[17] for the growth rate, g, discount rate, β, and depreciation, δ, to determine the rate of return on capital, r. I then use r and the base year quantities of output, capital/investment and energy, both for each sector, and emissions to

[17] Details given below for determination of g, β and δ.

solve for the remaining parameters. The following parameters are solved directly:

$$r = \frac{1+g}{\beta} - 1 + \delta \tag{4.7}$$

$$A^c = E^c / K^c \tag{4.8}$$

$$A^d = E^d / K^d \tag{4.9}$$

$$p^c = r / A^c \tag{4.10}$$

$$p^d = r / A^d \tag{4.11}$$

$$K^f = \frac{I}{\delta + g} - K^c - K^d \tag{4.12}$$

$$\alpha_k = \frac{rK^f}{Y} \tag{4.13}$$

$$\phi = \frac{M}{E^d} \tag{4.14}$$

Here, I is investment which is given as a share of output in the data (more on this below). The remaining parameters cannot be solved in closed form, therefore they must be solved jointly for the relevant parameters of interest (a, A^e, α_e and A^f) using a fixed point algorithm:[18]

$$a = \frac{p^d E^d}{pE} \tag{4.15}$$

$$p = \frac{p^d}{a} \left(\frac{C}{D}\right)^{1-\rho} A_e^{-\rho} \tag{4.16}$$

$$A^e = \frac{E}{(a(E^d)^\rho + (1-a)(E^c)^\rho)^{1/\rho}} \tag{4.17}$$

$$C = \left(\frac{1-a}{a} \frac{A^c}{A^d}\right)^{\frac{1}{\rho-1}} \tag{4.18}$$

$$D = A^e (aC^\rho + 1 - a)^{1/\rho} \tag{4.19}$$

$$\alpha_e = \frac{pE}{Y} \tag{4.20}$$

$$A^f = \frac{Y}{(K^f)^{\alpha_k} E^{\alpha_e}} \tag{4.21}$$

Overall, the parameter values needed to simulate the model are g, β, δ, A^c, A^d, a, A^e, α^e, α^k, A^f and ϕ. Each of these parameters is country-specific except the discount rate and depreciation. All parameter values are given in table 4.4 at the end of the section.

[18]For the fixed point algorithm, I make an initial guess for one of the parameter values (a). I then solve the remaining equations in the system with that guess and use those solutions to update the initial guess. The procedure is iterated until all parameter values have converged to a stable solution.

Data on output (in current USD), the fraction of "clean" energy (including nuclear),[19] GDP growth, investment and population are from the World Development Indicators (World Bank, n.d.). Energy and carbon emission data is from the Energy Information Administration (n.d.). Table 4.2 shows that GDP per capita, growth rate and investment ratios are similar for developed countries. There is more variation across developing countries, however there is a general trend that developing countries are more populous, poorer and growing more rapidly. In addition, India and China invest a considerably higher fraction of their output than all other countries considered here.

Table 4.2: Economic data (2012)

Country	Population	GDP per capita (2014 $US)	Growth rate (avg. 2009-2013)	Growth rate (model assumption)	Capital Formation (% GDP)
Brazil	198,656,019	11,320	3.4	3.0	18
China	1,350,695,000	6,093	8.8	7.0	49
India	1,236,686,732	1,503	6.7	7.0	31
Mexico	120,847,477	9,818	3.6	3.5	23
Russia	143,178,000	14,091	3.4	3.0	24
South Africa	52,274,945	7,314	2.8	3.0	19
Canada	34,754,312	52,409	3.2	2.0	25
France	65,676,758	40,908	1.2	1.5	23
Germany	80,425,823	43,932	2.1	2.0	21
Japan	127,561,489	46,679	1.9	1.5	21
U.K.	63,695,687	41,054	1.5	2.0	17
U.S.	313,873,685	51,496	2.2	2.5	20

The growth rate parameters used in the simulations were chosen based on recent performance with adjustments to account for forward looking expectations. In particular, China grew at an average rate of 8.8% per year from 2009 to 2013, however growth has slowed recently and the government has stated that lower growth near 7% can be expected going forward. Brazil and Russia's growth are also expected to decline significantly (probably lower than the 3% rate selected here). Among developing countries, the outlook in Canada has dimmed due to the severe drop in the price of oil in 2014 (the Bank of Canada has stated that it expects this to harm economic growth considerably). Meanwhile, the British and U.S. economies performed well in 2014 and therefore I chose higher growth rates than their averages from 2009-2013. However, it is important to note that the growth rate in the model represents the *long run* growth rate.

[19]The fraction of biomass energy is also obtained from the World Bank (n.d.). Biomass is removed from my calibration because it is generally a small share of energy and carbon policy is not expected to impact biomass energy (e.g. wood burning).

This is difficult to predict confidently looking forward. However, I intentionally select a range of growth rates in the simulations to allow for insight into how the growth rate affects the cost of reducing emissions. Furthermore, I perform sensitivity tests on the growth rate in section 4.3.3.

The initial capital stock is determined such that it grows at the steady state growth rate. That is, $(1 + g)K_0 = (1 - \delta)K_0 + I_0$ where I_0 is investment. The World Bank (n.d.) data gives investment as a fraction of GDP, thus the initial capital stock can be determined from the initial level output, the rate of investment, the growth rate and the rate of depreciation.

The capital stock of the energy sectors is based on the capital cost per unit of energy for each type of energy multiplied by the consumption of that type of energy; the energy types are then aggregated to clean and dirty. Capital cost estimates (per kW) for coal, oil and gas electric plants are from Davies (2009). For the dirty sector, I weight the capital cost values of coal, oil and gas plants according to the total consumption of those fuels in each country (weights are based on data from the Energy Information Administration (n.d.)). This gives the capital cost (per kW) for the dirty sector in each country. Thus I assume that capital costs for a given fossil fuel are the same for electricity generation and other uses. For the "clean" sector, the capital cost estimates for nuclear[20], hydro and alternative electricity generation are weighted according to their share of electricity for each country. This yields the capital cost (per kW) for the clean sector in each country.[21] The capital costs are converted to \$/ktoe, then are multiplied by total energy use in each sector to get the capital stock. This procedure assumes that the cost of a given type of power plant is constant across countries. I also perform robustness checks on the capital-energy ratio in section 4.3.3.

The discount rate β used for all countries is calibrated using a growth rate of 2.4% and a rate of return of 11% (≈ 0.975). I choose a rate of depreciation of 0.06 for all countries. Following Whalley and Wigle (1991), an elasticity of substitution between dirty and clean energy of 0.5 is prescribed for all countries. These parameters will be the subject of robustness checks in section 4.3.3.

Consistent with the discussion in section 4.1, the energy data used to calibrate the model shows considerable variation due to developmental, geographic and policy differences (see table 4.3).[22] For example, developed countries use much less energy per unit of GDP in general (although more energy per capita), but Canada and the U.S. have higher energy intensities

[20]It is clear that nuclear energy does generate dangerous waste, however I group it with the clean energy sources here because it does not generate carbon emissions.

[21]Note that these energy sources are only used in electricity generation, so there are no strong assumptions needed to link electricity and overall energy in the clean sector.

[22]I abstract from biomass energy for reasons stated earlier. This typically amounts to 2%-5% of the total share for developed countries, and 5%-10% for developing countries. However, Brazil and India are outliers using 29% and 25%, respectively.

Table 4.3: Energy data (2012, excluding biomass energy)

Country	Energy Intensity (10^{-7} ktoe/$)	% clean energy	CO_2/E^d (10^3 kt/ktoe)	K^d/E^d (10^5 $/ktoe)	K^c/E^c (10^5 $/ktoe)
Brazil	0.95	22.0	1.87	7.9	13.1
China	2.99	4.1	3.20	11.2	14.5
India	2.44	4.0	3.38	10.4	16.7
Mexico	1.58	6.5	2.38	7.8	16.7
Russia	3.91	8.3	2.27	8.5	21.9
South Africa	3.00	2.3	2.70	11.2	27.9
Canada	1.78	23.8	2.05	8.1	16.0
France	0.96	49.5	2.42	7.9	28.0
Germany	0.88	12.9	2.54	9.0	23.3
Japan	0.84	8.3	2.60	8.8	16.8
U.K.	0.80	11.0	2.37	8.6	25.8
U.S.	1.36	12.5	2.52	8.7	24.8

than other developed countries. This is partially due to greater automobile use which can be attributed to lower population density. Furthermore, many parts of Canada and the U.S. also experience hotter, more humid summers than moderate Europe leading to energy being consumed in cooling. Russia has a high energy intensity despite being much more developed than China and India, and Canada has a higher energy intensity than any other developed nation. This likely results from lower population densities and harsher winters and the consequent need for more heating during the winter months. There are also significant differences in the use of clean energy. France has the largest fraction of clean energy, which comes largely from a substantial share of nuclear electricity generation. Canada and Brazil have significant shares of clean energy due to large amounts of hydro-electric power. Germany has the highest proportion of alternatives at 10% of its total clean energy.

The CO_2/E_d ratio is determined by the mix of fossil fuels and the efficiency of their use. Brazil obtains virtually all of its fossil fuel energy from oil, which emits less CO_2 than the coal burned in China, India and South Africa. Russia and Canada have an abundance of natural gas, which results in lower emissions rates for dirty energy (natural gas is also a primary heating fuel for the winter). The capital-energy ratios, the inverse of which determines energy productivity in the model, are higher for countries that use more coal relative to gas and oil and more nuclear relative to hydro. This is a result of coal-fired plants being more expensive than gas and oil-fired plants, and nuclear plants being more expensive than hydro stations (alternatives are in between). These productivities are based on the cost of *building* power plants, not operating them. Thus the cost of the inputs (coal, oil, gas, uranium) is not taken into account. The cheaper cost of coal relative to oil may make coal plants cheaper overall. The sensitivity of the results to the capital-energy ratios is explored in the robustness section.

Note that in the model I do not allow countries to become more productive in dirty energy by switching away from coal, or more productive in clean energy by switching away from nuclear. This assumption is consistent with the notion that geography largely determines a country's fuel mix.

Table 4.4: Parameter values.

	g (%)	A^f $\times 10^3$	A^e	A^d $\times 10^{-6}$	A^c $\times 10^{-6}$	α_k	α_e	a	ϕ
Brazil	3.0	1.31	2.17	1.27	0.76	0.22	0.009	0.73	2.63
China	7.0	0.04	1.26	0.89	0.69	0.54	0.051	0.99	3.48
India	7.0	0.14	1.31	0.96	0.60	0.33	0.039	0.99	4.48
Mexico	3.5	0.77	1.68	1.28	0.60	0.26	0.015	0.96	2.49
Russia	3.0	1.26	2.03	1.18	0.46	0.25	0.039	0.91	2.29
South Africa	3.0	1.44	1.36	0.89	0.36	0.20	0.043	0.99	3.01
Canada	2.0	1.62	2.30	1.23	0.62	0.30	0.018	0.66	2.16
France	1.5	1.77	2.01	1.26	0.36	0.28	0.017	0.22	2.56
Germany	2.0	2.87	2.38	1.11	0.43	0.24	0.009	0.81	2.78
Japan	1.5	1.94	1.76	1.14	0.60	0.27	0.007	0.94	2.67
U.K.	2.0	3.70	2.46	1.16	0.39	0.22	0.008	0.83	2.45
U.S.	2.2	3.19	2.49	1.15	0.40	0.25	0.014	0.80	2.64

*Note: The following parameters are constant across countries: $\beta = 0.975$, $\delta = 0.06$, $s = \frac{1}{1-\rho} = 0.5$.

4.3 Simulation Results

Simulations of the 12 calibrated economies are performed in order to determine the loss of GDP associated with the implementation of a carbon tax.[23] To do this, the model is simulated for each country under a baseline scenario (no tax) and three carbon tax regimes such that the emissions are reduced by 10%, 25% and 50% (relative to the baseline scenario).[24] The tax rates needed to achieve the targeted reductions are different for each country due to varying energy intensities and carbon intensities of the dirty energy sector.

[23]The calibrated model is simulated over 100 years with an annual timestep. A shooting algorithm is used to solve for the dynamic solution to the model. For details on the shooting algorithm, see Appendix B.

[24]Note that emissions in this model always increase over time (even with a tax) due to the "balanced growth" nature of the model. In order to study the stabilization and/or reduction of emissions, the dirty energy sector could not grow, necessitating a different type of model. However, the balanced growth method adopted here is useful for cross-country comparisons and it is a standard approach in the literature.

The carbon tax raises the price of dirty energy, driving down its demand. If the prices of clean energy and capital were fixed, this would increase their demand because they become relatively cheaper. However, increased demand for clean energy and labour also pushes up their prices. Consequently, in equilibrium, there is a decrease in all inputs (except labour, which is fixed); this means output must fall. The relative change in the composition of inputs varies across countries depending on their energy intensities, capital intensities, growth rates and fuel mixes.

When the carbon tax is implemented, it knocks the economy off the balanced growth path. Growth is slowed because there is too much capital in the economy at the new higher prices. Investment slows to re-balance the capital stock in the new equilibrium. In the long run, the economy converges back toward the balanced growth path except at a lower level of output (and inputs) relative to the scenario with no tax. The growth rate is necessarily recovered asymptotically because it is determined by fixed parameters and the rate of return on capital which is asymptotically constant (see equation 4.7).

4.3.1 Long-run Analysis

Here I consider carbon taxes that result in emissions reductions of 10%, 25% and 50% compared to baseline (no tax). Tables 4.5, 4.6 and 4.7 report the percent change in the level of output, consumption, capital and energy at 35 years after the implementation of a carbon tax yielding each reduction target. The economies have approximately returned to balanced growth after 35 years, however there are slight differences in the timing of a return to balanced growth across countries. For these reasons (and because there is a lack of perfect numerical precision), the change in dirty energy, $\%\Delta E^d$, is not exactly the same as the emissions reduction target of 10%, 25% or 50% even though it is consistently very close. For example, for the 10% emissions reduction target, dirty energy is reduced by 9.95% to 10.46% relative to the baseline scenario after 35 years across countries (emissions are reduced by the same percentage).

Table 4.5 shows that for an approximate decrease in emissions of 10%, developing countries generally experience a much larger decrease in GDP than developed countries. The greatest loss for a developed country is 0.18% for Canada, which is lower than the loss for all but one developing country (Brazil). Among developing countries, Brazil and Mexico make out much better because their economies are relatively much less energy intensive. Furthermore, Brazil has a considerable share of clean energy. Meanwhile, China is the most severely impacted by a wide margin, losing 1.04% of GDP per year in the long run.

Developing countries tend to make out worse for three reasons. First, the clean energy sector is less able to compensate for the decrease in dirty energy. Developing countries (excluding

Table 4.5: 10% Emissions Reduction - loss in levels at 35 years

Country	$\%\Delta Y$	$\%\Delta C$	$\%\Delta K$	$\%\Delta E$	$\%\Delta E^d$	$\%\Delta E^c$
Brazil	-0.09	-0.02	-0.39	-7.40	-10.03	-3.82
China	-1.04	-0.31	-1.72	-9.51	-9.95	-5.34
India	-0.60	-0.17	-1.56	-9.88	-10.46	-5.35
Mexico	-0.19	-0.05	-0.66	-9.16	-10.43	-4.79
Russia	-0.45	-0.14	-1.47	-8.34	-10.13	-4.47
South Africa	-0.54	-0.16	-2.15	-9.64	-10.32	-5.20
Canada	-0.18	-0.06	-0.55	-6.97	-10.11	-3.63
France	-0.10	-0.03	-0.31	-4.02	-10.25	-2.08
Germany	-0.09	-0.03	-0.34	-7.43	-10.04	-3.82
Japan	-0.09	-0.03	-0.32	-8.79	-10.19	-4.54
U.K.	-0.08	-0.02	-0.33	-7.41	-10.02	-3.81
U.S.	-0.15	-0.05	-0.55	-7.54	-10.38	-3.91

Brazil), see a drop in total energy use between 8.34% and 9.88%; developed countries see a drop of 4.02% to 8.79%. This reflects the fact that most developed economies can substitute clean energy for dirty energy more easily. The countries with the biggest drop in total energy consumption are those with tiny clean energy sectors like India and China (even Japan to a lesser degree). Meanwhile France, with its considerable nuclear energy generation, sees a total energy drop of only 4.02%. Second, the reduction in energy usage has an outsized impact on output for countries that are more energy intensive. For example, India and China have similar reductions in energy usage, but India's loss of GDP is only 0.60% compared to 1.04% for China. This occurs because energy, which has been cut back, makes a larger contribution to each unit of output in China. The third factor is the reduction in capital which comes from much higher prices in the face of higher demand from substituting away from more expensive energy. The reduction in capital depends on the capital intensity of the economy as well as the growth rate (which affects the return on capital). A higher capital intensity or growth rate results in a greater drop in capital levels. For example, China's energy consumption is reduced by 9.51% compared to 9.88% in India,[25] but China's capital level is reduced by 1.72% compared to 1.56% for India because China is more capital intensive. Meanwhile, Brazil and Germany have similar reductions in energy uses, but Brazil's drop in capital is greater. Brazil has a lower capital intensity but a higher growth rate. Here, the effect of the growth rate overcome the capital intensity effect. This shows that, all else being equal, the higher growth rates of developing countries result in larger drops in capital levels as a consequence of the carbon tax, which negatively impacts output. Finally, note that consumption losses are about 1/4 to 1/3

[25]For both I assume a 7% growth rate.

less than output losses as there is a reduction in investment associated with the lower levels of capital required in the new 'tax' equilibrium. A portion of output that had been directed toward investment is now consumed.

Tables 4.6 and 4.7 show the decrease in inputs and output associated with emissions reductions of 25% and 50%, respectively. Of note, the losses do not scale linearly with the emissions reduction (not surprising considering the production function is nonlinear). The 50% reduction results in twice the reduction in emissions of the 25% target, but causes the output losses to more than double. For example, Mexico's output loss increases from 0.50% to 1.22% and Canada's loss increases from 0.50% to 1.23%.

Table 4.6: 25% Emissions Reduction - loss in levels at 35 years

Country	$\%\Delta Y$	$\%\Delta C$	$\%\Delta K$	$\%\Delta E$	$\%\Delta E^d$	$\%\Delta E^c$
Brazil	-0.26	-0.10	-1.00	-19.28	-25.19	-10.27
China	-2.84	-1.02	-4.53	-24.13	-25.09	-14.07
India	-1.60	-0.54	-3.92	-24.23	-25.47	-13.65
Mexico	-0.50	-0.18	-1.63	-22.54	-25.25	-12.21
Russia	-1.22	-0.45	-3.78	-21.19	-25.13	-11.76
South Africa	-1.44	-0.52	-5.35	-23.71	-25.15	-13.28
Canada	-0.50	-0.20	-1.44	-18.29	-25.37	-9.82
France	-0.27	-0.11	-0.83	-10.87	-25.16	-5.71
Germany	-0.25	-0.10	-0.91	-19.40	-25.47	-10.34
Japan	-0.25	-0.10	-0.80	-22.15	-25.22	-11.87
U.K.	-0.21	-0.09	-0.84	-19.32	-25.19	-10.27
U.S.	-0.39	-0.15	-1.37	-18.92	-25.08	-10.13

4.3.2 Transition path

The analysis above illustrates the long term impact of a carbon tax after the economy has returned to steady state. However, the effect of the (unexpected) tax in the short run is to knock the economy out of balance; as such, the economy is no longer operating efficiently. During this period, losses are even greater than in the long run because the economy cannot grow at its efficient long run rate.

Figures 4.6 and 4.7 show the growth rates for all countries under the different reduction targets. In all cases, the growth rate is initially lowered in the aftermath of the implementation of the tax, with higher taxes causing more significant declines in the tax rate. In the long run (over 35 years), the growth rate re-converges toward the balanced growth rate as the economy rebalances in the presence of the tax. As would be expected, countries that are worse off in the

Table 4.7: 50% Emissions Reduction - loss in levels at 35 years

Country	$\%\Delta Y$	$\%\Delta C$	$\%\Delta K$	$\%\Delta E$	$\%\Delta E^d$	$\%\Delta E^c$
Brazil	-0.64	-0.29	-2.17	-41.10	-50.13	-23.50
China	-6.71	-3.15	-9.98	-48.51	-49.93	-30.57
India	-3.76	-1.70	-8.30	-48.33	-50.13	-29.47
Mexico	-1.22	-0.58	-3.49	-46.33	-50.35	-27.18
Russia	-2.94	-1.41	-8.09	-44.11	-50.04	-26.33
South Africa	-3.44	-1.63	-11.19	-48.02	-50.15	-29.15
Canada	-1.23	-0.61	-3.15	-39.19	-50.06	-22.48
France	-0.71	-0.35	-1.96	-26.08	-50.04	-14.32
Germany	-0.62	-0.31	-1.97	-41.29	-50.20	-23.61
Japan	-0.60	-0.30	-1.71	-45.52	-50.08	-26.40
U.K.	-0.53	-0.25	-1.84	-41.17	-50.13	-23.50
U.S.	-0.99	-0.47	-3.03	-40.97	-50.45	-23.55

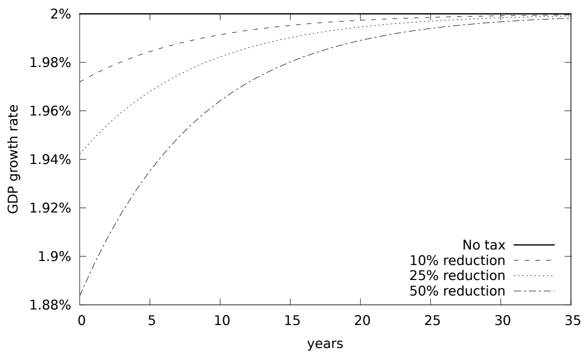
long run are also worse off in the short run. Under the 50% reduction scenario, China's growth rate initially falls from 7% to 6.5% and is much slower to return to the long run growth rate than other countries. Brazil's growth rate falls only from 3% to 2.92% and returns to 2.99% after about 15 years. Amongst developed countries, Canada experiences the most significant drop, from 2% to 1.88%; Japan experiences a minuscule fall from 1.5% to 1.44%. Japan's growth also converges more quickly to the steady state rate than that of Canada.

4.3.3 Robustness Checks

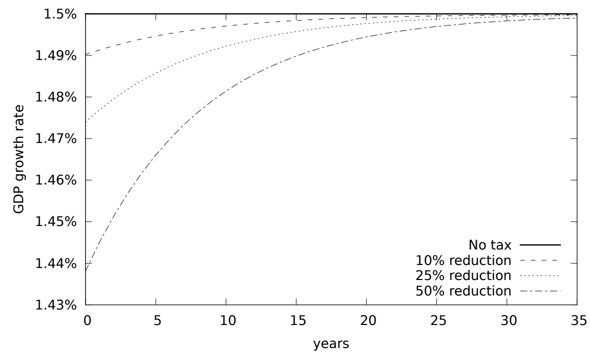
There are four data values/parameters about which strong assumptions were made in the model calibration. These are the growth rate, the elasticity of substitution between dirty and clean energy and the capital-energy ratios (dirty and clean).[26] Here, I check the sensitivity of the results to these assumptions. Since China faces the greatest losses from reducing emissions in my model, I perform the sensitivity analysis using the Chinese case (under the 50% emissions reduction policy).

I find that lowering the growth rate and the elasticity of substitution between energy sources has a material impact on the model results (both result in lower losses). However, raising those parameter values has a relatively small impact on the results. In terms of the capital costs of energy, changing the cost of clean energy has very little impact but changing the cost of dirty energy has a considerable impact. Changes to clean energy costs are likely to have more impact on countries with larger clean energy sectors than China.

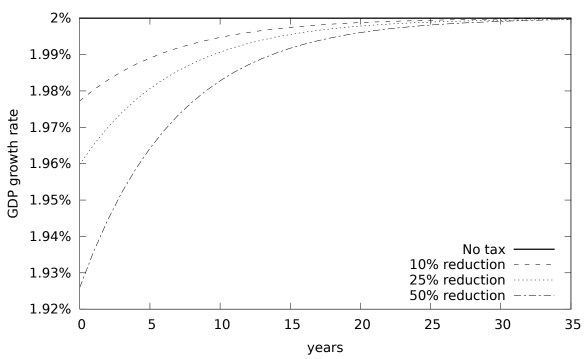
[26] I do not perform checks on the depreciation and discount rate for reasons explained below.



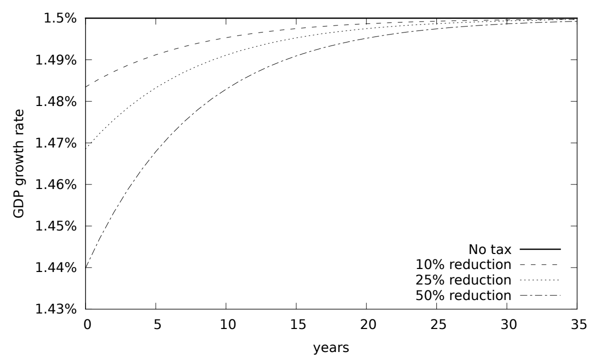
(a) Canada



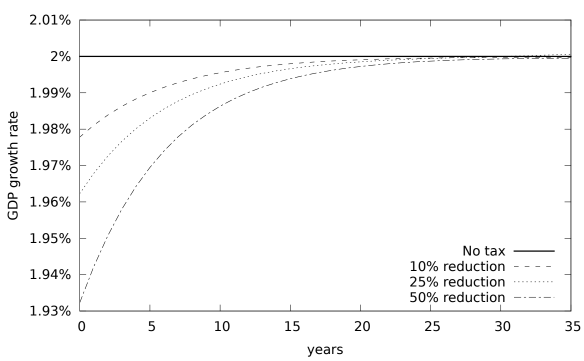
(b) France



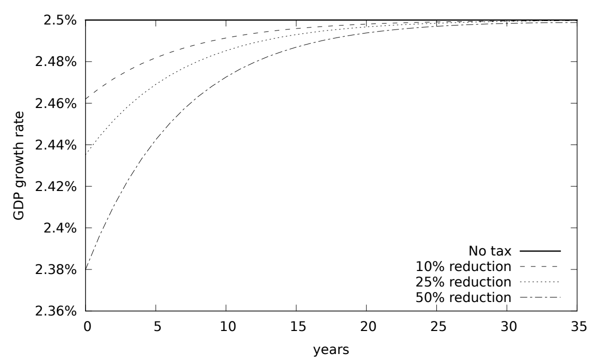
(c) Germany



(d) Japan

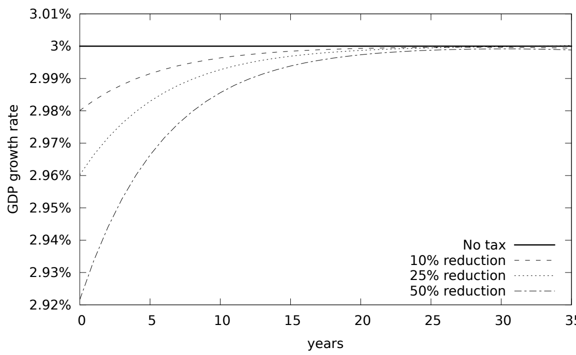


(e) U.K.

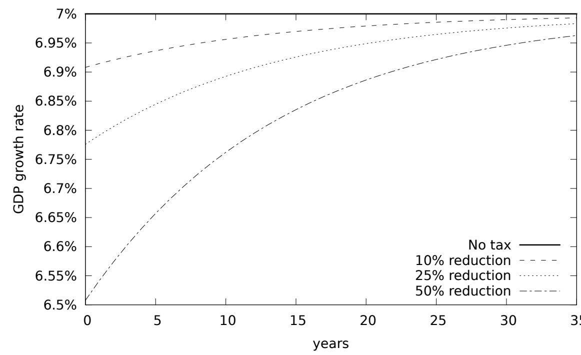


(f) U.S.

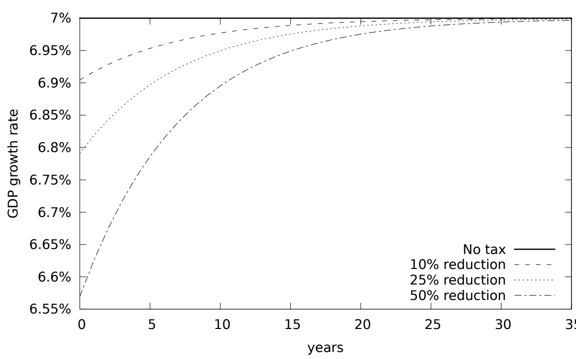
Figure 4.6: Developed countries growth rates



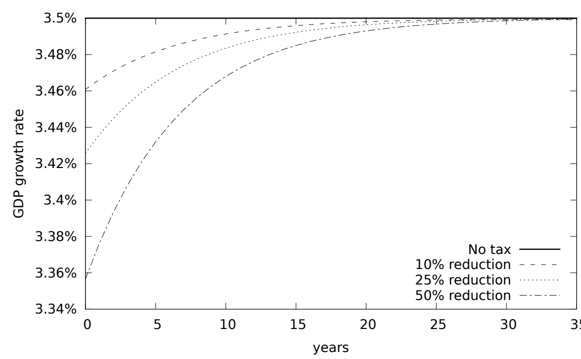
(a) Brazil



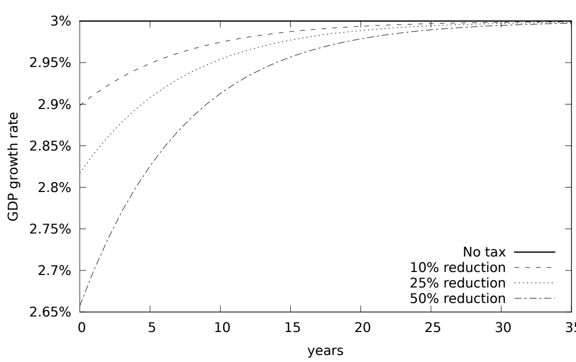
(b) China



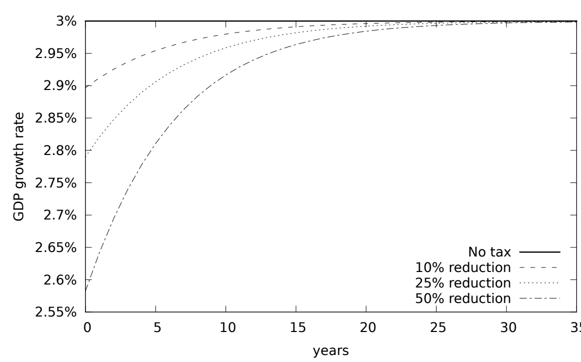
(c) India



(d) Mexico



(e) Russia



(f) South Africa

Figure 4.7: Developing countries growth rates

Note that in the model, the growth rate, along with depreciation and the discount factor, determine the rate of return. The growth rate and depreciation determine consumption along the balanced growth path. These parameters affect no other variables *directly*. Therefore I will only vary the growth rate, which will in turn vary the rate of return and consumption. It is not necessary to vary the depreciation and discount rate since this could be achieved through an appropriate variation in the growth rate.

Growth Rate and Elasticity of Substitution

In the calibration of the model, I chose China's long run growth rate to be 7%, in line with guidance provided by the central government. However, there is considerable uncertainty over what China's long run growth rate might be.[27] Prior to the financial crisis, China had been experiencing growth well above 10% for five years in a row. In the aftermath of the crisis, growth was between been between 9% and 10%, then falling below 8% the past two years. I test the model with a growth rate of 10% to study the impact of reducing emissions if China returns to the type of growth it had seen since the turn of the century.

However, if China continues to grow rapidly, its growth rate may be expected to converge to that of a developed country as GDP per capita approaches that of a developed country (similar to other countries that have already gone through the development process). Therefore, I also test a growth rate of 3%. For China, it may be unlikely that growth will drop as low as 3% in the near term, but but this represents a long-run growth rate.

Table 4.8 shows how the inputs and output changes under different growth scenarios after China re-converges to the balanced growth path. This does not occur at the 35 year mark, which was presented earlier to be consistent across all countries. China re-converges closer to 40 years, depending on the tax and growth scenario. Under 10% growth, there is very little change to the results compared to 7% growth.[28] However, under the low growth scenario, the annual output loss drops from around 7% to 6%. This results from a smaller drop in the level of capital. For a lower growth rate, the economy is calibrated with a larger capital share of income and a lower return on capital. Thus capital is less costly than in the higher growth scenario and there is more relative substitution toward it.

For the baseline calibration, I chose an elasticity of substitution between dirty and clean energies of 0.5. This is a common choice in the literature (e.g., see Whalley and Wigle, 1991). However, while most estimates are in this range and always less than 1, empirical elasticity estimates often suffer from a lack of statistical significance. Therefore, I run the model using elasticity parameter values of 0.25 and 0.75 to test the sensitivity of the model to the elasticity

[27] Uncertainty about the long run growth rate exist for all countries, especially developing ones.

[28] Due to numerical precision issues, dirty energy is not reduced by exactly 50% in any scenario.

Table 4.8: 50% Emissions Reduction Losses, Different Parameter Assumptions (China)

Scenario	$\%\Delta Y$	$\%\Delta C$	$\%\Delta K$	$\%\Delta E$	$\%\Delta E^d$	$\%\Delta E^c$
Baseline (g = 7%, s = 0.5)	-7.17	-3.75	-10.73	-48.94	-50.35	-31.14
g = 10.0%	-6.96	-3.63	-10.49	-48.32	-49.75	-30.31
g = 3.0%	-5.97	-3.55	-8.48	-48.73	-50.17	-30.56
s = 0.25	-4.66	-2.40	-7.17	-49.02	-50.12	-40.38
s = 0.75	-7.19	-3.78	-10.74	-48.19	-50.15	-19.76

choice.

Table 4.8 shows the change in inputs and output for the different choices of elasticity. Moving the elasticity from 0.5 to 0.75 causes the drop in clean energy to go from 31% to 20%. This is what is expected for a higher elasticity; it is easier to substitute cleaner fuels when the price of dirty fuels goes up. However, this has a very small impact on overall energy and hence very little impact on output. Reducing the elasticity from 0.5 to 0.25 has the opposite effect on clean energy as the reduction goes from 31% to 40%. However, this ends up feeding through to output in a much more substantial way. The output loss drops from 7% to 4.7% because the capital stock is maintained at a higher level.

The Capital-Energy Ratios

The capital energy ratios are used to determine the capital stock of each energy sector. This in turn determines the productivity (and prices) of dirty and clean energy. In the initial calibration, I weighted the values of capital costs of different power plants by fuel type for each country. There are two potential issues here. First, this assumes that the capital costs of power plants are the same in every country. Second, and more importantly, for dirty energy it assumes that the capital costs of non-electric energy are the same as for electric energy.[29]

To quantitatively assess the importance of these assumptions, I test two new values for the capital costs of both clean energy and dirty energy. For each energy type, I consider a doubling and halving of the capital-energy ratio. Note that in the model I also implicitly assume that the capital costs of energy are fixed, so this will also give a sense of how decreasing costs could affect the results (see table 4.9).

Halving the capital cost of clean energy results in a slightly larger reduction in clean energy and hence a slightly larger reduction in output (from 7.17% to 7.34%). This may seem counter-intuitive, but recall that the economy is initially considered to be on the balanced growth path. The economy still uses the same initial fuel mix despite clean energy becoming cheaper, and

[29]I also do not consider the input costs of power plants in this study.

Table 4.9: 50% Emissions Reduction Losses, Different Energy Costs (China)

Scenario	$\%\Delta Y$	$\%\Delta C$	$\%\Delta K$	$\%\Delta E$	$\%\Delta E^d$	$\%\Delta E^c$
Baseline	-7.17	-3.75	-10.73	-48.94	-50.35	-31.14
$K/E^C \times 2$	-6.81	-3.59	-10.23	-47.26	-50.17	-29.88
$K/E^C \div 2$	-7.34	-3.72	-10.99	-49.53	-50.23	-31.63
$K/E^D \times 2$	-12.62	-6.59	-18.89	-49.99	-49.35	-33.47
$K/E^D \div 2$	-3.71	-1.93	-5.56	-47.38	-50.43	-28.82

the elasticity of substitution remains the same. Therefore it will take an even greater movement in the relative energy prices (i.e. a larger tax) to drive substitution toward clean energy under the new calibration. When the capital cost of clean energy is doubled, the opposite effect is seen and the output loss drops from 7.17% to 6.81%. These are relatively minor effects, although countries with more clean energy would probably see more significant impacts.

Modifying the capital costs of dirty energy has a much more substantial impact on the results for China. Halving the capital cost of dirty energy results in a substantial drop in the loss of capital and hence output (from 7.17% to 3.71%). This is again because the initial price of dirty energy is recalibrated to reflect the lower cost of capital while the fuel mix remains the same. This drives down the total price of energy and hence as the price goes up, it is easier to substitute for capital under the new calibration. Accordingly, increasing the capital costs of dirty energy substantially increases the loss of output from a carbon tax, with the loss rising to 12.62% of GDP. This demonstrates that if building coal power plants is much cheaper in China (and other coal dependent developing countries) than in developed countries, then the cost of reducing emissions may be lowered considerably, and vice versa.

4.4 Discussion

The main challenge facing international climate change treaty negotiations is how to incorporate developing countries. It has been argued that developing countries cannot make the same types of emissions reductions as developed countries because it is more costly for them to do so. Yet, developing countries are expected to account for the majority of future emissions, therefore any successful treaty must include them.

This paper has presented data showing that developing countries tend to be more energy intensive and have more carbon-intensive fuel mixes. Using an energy-economy model, I have found that due to higher energy and carbon intensities, developing countries face significantly greater GDP losses than developed countries from reducing carbon emissions via a carbon tax. For example, for a 25% reduction in emissions, developed countries lose at most 0.5% from the long-run GDP level, whereas developing countries (other than Brazil and Mexico) lose 1.2% to 2.8%. Mexico loses 0.5% and Brazil loses 0.3% as they both have relatively low energy intensity economies for developing countries.

Focusing on the largest emitter and the most sensitive country to emissions reductions, I find that China's GDP level is lowered by 2.8% and 6.7% for reductions in emissions of 25% and 50%, respectively. These losses are higher than the results given in previous studies. Zhang (1998a,b, 2000) found that for China, GNP is lowered by 1.5% and 2.8% for carbon reductions of 20% and 30%, respectively. Wang et al. (2009) found that a 50% reduction in emissions leads to a 6.19% loss in GDP. These models have multiple sectors and technological improvement which may lead to lower losses. I discuss this more below.

There are some implicit assumptions in my model which may affect my results. First, I assume that the structure of each energy sector is fixed. That is, I do not allow substitution from coal to gas nor from nuclear to hydro, or vice versa. However, geographic considerations may limit this type of substitution in many cases. For example, natural gas requires pipelines as it is expensive to transport in liquefied form, hence the cost for a country like China to vastly increase its share of natural gas might be prohibitive. Similarly, the potential for hydro power, wind power and solar power depend considerably on geography. Second, I do not allow for technological improvement in energy efficiency (beyond economy-wide productivity gains). Developed countries have begun to see a decoupling between economic growth and energy consumption, and it would not be unreasonable to assume that developing countries will do the same as a result of technological improvement (and economic development). Third, I have only one final good sector in my model which does not allow for sectoral reallocation. For example, heavy industry consumes much more energy than light manufacturing. If a country could reallocate resources away from energy intensive sectors, the GDP losses from reducing emissions would not be as great. Fourth, if the carbon tax acted to alleviate market inefficiencies, losses would be reduced, which might be especially relevant for China (Garbaccio et al., 1999).

The above considerations would lead to smaller losses than reported in this paper. However, there are factors that may act in the opposite direction. In my results, there is a very rapid adjustment of the capital stock in the first period away from dirty energy and toward clean energy. This type of massive adjustment in one year is likely impossible. Slowing the ability to reallocate capital would result in greater losses from reducing emissions.[30] Finally, I do not have trade in my model, which could be important in assessing the impact of emissions reductions. For example, if a developing country has a comparative advantage in energy intensive goods, then a carbon tax will diminish that advantage and possibly do significant damage to

[30]This could be done in a model with capital adjustment costs for firms.

exports.

In this study, the gap in the costs of reducing emissions between developed and developing countries is significant. This implies that transfers from developed to developing countries will be needed to secure a climate treaty. Babiker et al. (2000) used a multi-sector, multi-region model to determine the transfers needed to offset the costs that would be imposed by the Kyoto protocol on developing countries via trade linkages.[31] They found that if OECD countries compensated developing countries directly for losses, the annual transfer would be about $25US billion (about 2% of Chinese GDP when the study was published in 2000). However, this study assumes no action by developing countries, which will be necessary moving forward beyond the Kyoto protocol. Focusing only on the most impacted country in this study, 6.7% of China's 2013 GDP is $619B USD (corresponding to the loss from a 50% reduction in emissions); however this paper does not account for the benefits of climate change avoidance so that number would likely be a ceiling on a transfer required to induce climate treaty participation. As of 2011, $32B had been pledged by developed countries to help developing countries with climate change adaptation and mitigation (Climate Funds Update, n.d.). My results indicate that it is likely this figure will have to rise significantly in order to induce developing countries to make significant emissions cuts.

[31] The Kyoto protocol called for most developing countries to reduce emissions by 15%-30%.

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Chapter 5

Conclusion

This thesis has examined three topics relating to climate change. In Chapters 2 and 4, I studied the cost of implementing climate policy in developing countries as it relates to the sectoral composition of the economy in general terms and with regards to the energy sector specifically. Chapter 3 investigated the economic impacts of flooding at the city level, motivated by the threat of more frequent and severe flooding as a result of climate change.

In Chapter 2, I quantified the anticipated impact of structural change on carbon emissions intensity in China, along with a less detailed examination for other developing countries. To do so, I developed a 2-sector (industry and services) non-balanced growth model that uses energy as an input to production, with services being less energy intensive than industry (and thus less emissions intensive). I calibrated the model to the Chinese economy, and I also performed "rough calibrations" of the model to other large developing economies. I found that faster structural change leads to significantly greater reductions in emissions intensity for China. I also found that structural change materially reduces China's loss of GDP incurred from implementing a carbon tax. Comparing across a group of large developing countries, those with smaller service sectors see a greater decline in emissions intensity over the next 30 years. This makes it less costly for them to make emissions intensity reductions.

This result demonstrates that estimates of costs associated with climate policies could be significantly overstated if structural change is not accounted for properly. This has important implications for international climate change treaty negotiations. In Chapter 4 I showed that transfers from developed countries to developing countries will likely be needed to induce participation in a climate treaty. It could be important to consider the current size of the service sector when allocating funds because developing countries that already have large service sectors may find it much harder to reduce emissions.

Chapter 3 established a framework for quantifying the economic costs of flooding at the local level. We developed a dynamic multi-sector computable general equilibrium (CGE) model to determine the economic impact of a flood and the subsequent rebuilding. The flood is modelled as a shock to the capital stock, with damage varying across sectors depending on geographic location. The economy restores the capital stock through investment determined by market prices for capital.

As an application of the model we considered a flood of Metro Vancouver, for which we assembled new data (local input-output and final demand tables). The most exposed sector to flooding in our scenario was Transportation and Warehousing because the airport and a large seaport are situated in the flood plain. The Manufacturing and Wholesale Trade sectors were the other most impacted sectors. Construction and Manufacturing recovered rapidly because they are essential to rebuilding and replacing damaged equipment. The capital stock of capital-intensive industries initially declined after the flood damage because their marginal product of capital became smaller than other industries and thus there was little investment to replace depreciated capital.

This new approach to modelling flood impacts is more flexible and requires fewer assumptions than the current benchmark approach of input-ouput modelling. It also has novel elements compared to other CGE models, in particular it is fully dynamic so assumptions on investment are not needed (and investment is key to the recovery). We also presented a straight-forward methodology for estimating the initial flood damage based on employment data across municipalities. This new framework can help cities decide between policy options (like diking or relocation) in the face of future flooding based on climate change scenarios.

In Chapter 4, I studied the relationship between the energy sector and the cost of reducing carbon emissions, contrasting developed and developing countries. I documented facts about energy consumption across countries and over time. For the most part, more developed economies are more energy efficient and total energy consumption is rising much more rapidly in most developing economies. Variations in fuel mix are driven by geography and policy.

I used an energy-economy model to study how GDP is affected by lowering emissions via a carbon tax. The model accounts for the economy's energy intensity and fuel mix by using composite energy as an input to production where composite energy is composed of "clean" and "dirty" energies. I calibrated and simulated the model for six developing countries and six developed countries. I found the higher energy intensity and dirtier fuel fix of most developing countries make it much more costly for them to reduce emissions.

Because it is more costly for many developing countries to lower emissions (particularly the major emitters China and India), they will find it difficult to make the same level of emissions reductions as developed countries. This is a problem because developing countries are expected to contribute the majority of future emissions. Consequently, transfers from developed to developing countries are likely needed to reach an optimal level of global emissions.

This has been a major issue in climate treaty negotiations to date.

The results of Chapter 2 on structural change do not negate the results of this paper. For China, with a relatively small service sector, structural change reduces the cost of lowering emissions by less than half; this would still make China's costs considerably higher than developed countries. India has a larger service sector therefore the savings from structural change are even smaller. The results in this thesis on structural change and the energy sector complement each other to help identify countries that are likely to face the greatest difficulties in reducing emissions and thus where more effort must be focused to mitigate potentially dangerous climate change.

Appendix A

Input-output and final demand tables (Chapter 3)

The Metro Vancouver input-output and final demand tables, derived as explained in the paper, are given below. The sector definitions can be found in tables 3.1 and 3.2. Note that while the tables are derived with separate investment for the private sector and government, these two forms of investment are merged in the model calibration.

Table A.1: Metro Vancouver Input-output table (continued on next page).

	B11	B21	B22	B23	B31	B41	B44	B48	B51	B52
B11	98	2	2	20	834	4	3	11	3	11
B21	6	124	32	472	704	24	25	29	4	36
B22	16	55	3	27	410	34	75	90	34	168
B23	15	43	165	28	50	28	58	214	21	967
B31	321	470	36	4,303	6,015	347	259	2,072	630	635
B41	45	78	10	609	694	117	112	189	122	153
B44	13	23	7	221	246	48	69	76	54	81
B48	70	96	9	268	1,092	331	267	2,419	145	467
B51	13	27	5	60	126	269	195	182	933	751
B52	90	240	85	601	761	689	1,288	881	386	5,807
B54	42	167	23	1,291	207	383	401	218	265	1,286
B56	33	57	14	123	104	213	235	281	187	1,217
B61	0	0	0	5	0	4	10	2	25	13
B62	0	0	0	0	0	0	0	0	0	5
B71	1	3	1	7	25	33	26	12	56	41
B72	4	16	4	15	74	68	72	173	69	149
B81	14	15	2	41	56	19	21	143	58	218
G61	1	3	0	23	6	7	11	8	7	21
G62	1	1	0	1	3	5	5	4	5	14
G91	8	11	2	45	57	53	67	78	42	220
Net tax on products	3	28	4	187	96	42	45	-357	-11	526
Net tax on production	30	22	145	162	189	230	217	269	-22	2,740
Labour costs	461	431	824	4,241	6,264	3,596	4,049	4,021	1,965	5,872
Capital costs	314	2,009	1,303	2,677	2,889	1,475	1,615	2,138	2,830	20,896
TOTAL	1,599	3,921	2,677	15,430	20,901	8,017	9,126	13,153	7,807	42,295

Table A.1: Metro Vancouver Input-output table (continued).

	B54	B56	B61	B62	B71	B72	B81	G61	G62	G91
B11	6	2	0	1	2	32	3	1	3	44
B21	8	4	1	3	2	6	15	11	4	6
B22	44	12	5	46	15	57	114	29	21	63
B23	26	13	2	30	10	22	56	134	68	195
B31	490	329	29	264	130	1,129	560	244	407	684
B41	147	64	5	54	27	162	105	42	97	178
B44	90	49	5	42	180	246	92	42	85	186
B48	221	95	11	57	30	66	154	106	27	340
B51	388	134	9	136	41	87	129	90	47	140
B52	712	303	61	412	142	588	499	26	26	332
B54	977	203	15	106	61	102	150	69	27	536
B56	341	130	17	62	64	134	196	45	75	481
B61	13	4	1	8	1	6	4	4	2	41
B62	0	0	0	3	0	0	0	2	414	1,666
B71	17	12	1	3	75	39	27	4	2	39
B72	149	53	6	28	35	37	69	35	29	64
B81	107	81	8	70	48	41	86	24	75	180
G61	26	3	1	5	4	4	8	7	1	31
G62	11	3	1	2	2	2	5	1	3	216
G91	66	18	5	30	19	36	62	17	56	418
Net tax on products	-162	54	3	-25	1	97	66	55	41	63
Net tax on production	66	59	6	28	26	127	54	0	0	24
Labour costs	4,801	1,917	207	1,502	578	2,250	2,814	4,441	2,452	5,370
Capital costs	2,131	832	95	1,330	347	508	618	890	291	1,705
TOTAL	10,675	4,375	494	4,199	1,839	5,780	5,886	6,321	4,255	13,002

*Note: Sector definitions can be found in tables 3.1 and 3.2.

Table A.2: Metro Vancouver final demand table.

	Consumption	Government	Investment (private)	Investment (government)	Exports	Imports	Total
BS11	769	0	3	2	1,063	-1,322	515
BS21	131	0	463	47	3,232	-1,469	2,404
BS22	1,280	0	23	9	392	-345	1,358
BS23	44	0	10,505	2,833	69	-167	13,284
BS31	12,956	0	3,306	519	22,266	-37,501	1,546
BS41	3,137	0	447	140	4,565	-3,284	5,004
BS44	6,906	0	244	43	1,474	-1,397	7,270
BS48	2,402	0	99	16	9,592	-5,229	6,881
BS51	2,431	0	337	90	3,559	-2,371	4,045
BS52	24,661	0	1,811	19	8,149	-6,274	28,366
BS54	498	0	1,072	258	5,427	-3,111	4,146
BS56	316	0	21	11	1,380	-1,360	367
BS61	285	0	2	1	94	-31	351
BS62	1,828	0	10	6	386	-121	2,108
BS71	1,516	0	6	3	838	-946	1,417
BS72	4,844	0	3	1	3,171	-3,389	4,630
BS81	4,488	0	27	7	645	-586	4,581
GS61	923	4,616	294	281	494	-466	6,142
GS62	351	3,770	4	1	220	-378	3,968
GS91	934	14,284	63	34	373	-3,997	11,692
Sales tax	5,864	0	1,234	42	149	304	7,593
TOTAL	76,564	22,669	19,975	4,362	67,538	-73,441	117,667

*Note: Sector definitions can be found in tables 3.1 and 3.2.

Appendix B

Shooting algorithm

The models used in Chapters 2 and 4 feature endogenous investment, which means that at any period in time the household chooses quantities (consumption and investment) covering two periods.[1] That is, the solution to the model in period t interacts with the solution in period $t+1$. As a result, the optimal solution to the model cannot be solved for in a single period and recursively iterated through time. Since the model has an infinite time horizon over which the household maximizes utility, the transversality condition is needed to close the solution:

$$\lim_{t\to\infty} \beta^t u'(c_t) k_{t+1} = 0 \tag{B.1}$$

The transversality condition ensures that the value of the capital stock, in terms of discounted utility, goes to zero in the limit (i.e., capital does not asymptotically dominate consumption). The "balanced growth" solution to the model is a consequence of the transversality condition.

For numerical simulation purposes, a condition holding as $t \to \infty$ cannot be implemented. Instead, I use the shooting algorithm to solve for the dynamic solution to the model, which takes advantage of the fact that the model converges toward the balanced growth path in the limit. The shooting algorithm involves making an initial guess for consumption, C_0', and solving the model recursively based on that guess. That is, given C_0 and k_0, I can solve for k_1 using the market clearing condition for the final good:[2]

$$k_{t+1} = Y_t - C_t + (1-\delta)k_t$$

The value of k_1 allows for solving other variables in the model at $t = 1$, including r_1. Then the Euler equation from the household problem can be used to solve for C_1:

[1]Note that the model in Chapter 2 is discretized using the Euler method before the shooting algorithm is applied.

[2]Y_1 can be solved for using k_0.

$$C_{t+1} = \beta(1 + r_{t+1} - \delta)C_t$$

With values for k_1 and C_1, the same procedure can be used to solve for k_2 and C_2 and subsequently the entire dynamic timepath of the model.

Depending on whether the resulting solution for the capital stock as t gets large diverges above or below the balanced growth path value, the consumption guess is updated to a higher or lower value, C_0'', and the entire timepath of the model is solved once again. This process is iterated using a bi-section algorithm for C_0 until a stable solution is found where k converges toward the balanced growth path. That is, $k_{t+1} = (1 + g)^t k_0$ for large t.

While the shooting algorithm works as intended, the simulations are very sensitive numerically.[3] A balanced growth path can always be determined to several digits of numerical precision, but for t sufficiently large the solution destabilizes and diverges away from balanced growth rapidly. This can happen in as quickly as 65 years, or after hundreds of years, depending on the simulation parameters. This occurs because extreme precision is needed for the initial guess, C_0, to get a numerical solution that solves the model for a large number of consecutive time periods. Rounding error also plays a role in the lack of precision and destabilization. This numerical sensitivity does not affect the interpretation of the results during the time horizon for which I am interested (roughly the first 40 years in both Chapter 2 and 4).

[3]The simulations are programmed in Fortran and run on a Linux machine.

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