Essays on Energy Economics
Advanced Modeling Approaches and Policy Analysis

Doctoral Thesis

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Essays on Energy Economics: Advanced Modeling Approaches and Policy Analysis

A thesis submitted to attain the degree of

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The more we do,
the more we can do;
the more busy we are,
the more leisure we have.
— William Hazlitt

To my parents. . .

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This is the last moment of my disseration writing. When looking back over the years I have stayed in the chair to write my dissertation, I find it has been the most fruitful journey that I have ever made in my life. It would not have been possible to write this doctoral thesis without the help and support of the kind people around me. I am using this opportunity to express my gratitude to everyone who supported me throughout my doctoral studies.

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Zurich, Nov. 2014   L.Z.

Abstract

Economic models are an important tool for evaluating the potential impact of proposed energy policies on the economy. The use of model-based analysis and scenarios in energy policy design and assessment has been growing in the last decades. Nowadays, many national government and inter-governmental bodies make use of the results from economic models for policy design. These models offer policy makers an effective understanding of the potential economic cost and benefits of mitigating carbon emissions. Sound modeling results guide decision making in energy and climate policies in a direction of maximizing the effectiveness of the economic effort.

Economic growth is driven by the accumulation of capital stocks. In endogenous growth models, technological knowledge is treated as a form of capital that is accumulated through research and development (R&D) and other knowledge creating processes. This type of models allows for an analysis of the economic growth effects of energy policy in the long run. Moreover, an important aspect of energy and climate policies is technology development, which can be studied by looking into the capital accumulation process. The first part of the thesis develops the macroeconomic modeling framework to analyze the growth effects of energy policies in the regional economy.

Chapter 2 extends the one country multi-sector endogenous growth model to represent various electricity generation technologies and fossil energy sources in the energy sector. The newly extended energy model part features rich technology details as in bottom-up energy sector models. However, it avoids to some extent the computational complexities involved in solving two hard-linked models. With the simplified bottom-up module, Chapter 2 studies the effects of nuclear phase-out policies in Switzerland. It shows that an economy can cope well with ambitious energy policies through sufficient innovation. Chapter 3 employs the same model for further discussion on some crucial elements in macroeconomic model analysis. One of the main focal points is the institutional concerns regarding the distributional principle between today and future generations.

From the perspective of applied macroeconomics, it seems rewarding to inquire into the restricted input use in a high-growth economy to derive the dynamic impact and the size of its effects. However, to develop a fully endogenous growth model is theoretically and

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numerically demanding. Chapter 4 shows the possibility of constructing such dynamic model and its application to China. The framework includes disaggregated industrial and energy sectors, endogenous innovation, and sector-specific investments. For the long run up to 2050, the paper shows that welfare costs of emission reduction for China lie between 3 and 8 percent. The cost can be reduced significantly through faster energy technology development, stronger induced innovation, and rising energy prices in the reference case. Furthermore, increased urbanization raises the costs of carbon policies due to altered consumption patterns.

On a global scale, induced changes in international knowledge transmission become important when one evaluates the effects of global energy policies. Energy policies could induce additional knowledge creation and diffusion, counteracting the negative cost effects of higher energy prices. Hence, Chapter 5 presents a multi-region multi-sector endogenous growth model with the inclusion of international knowledge for this purpose. This chapter enables a detailed study of the impacts of global climate policy on knowledge and growth.

The last part of the thesis is composed of two empirical papers. If macroeconomic models are powerful in evaluating the potential cost of energy policies, econometric models are preferred in estimating the effects of energy policies which have already been implemented. In recent years, the Chinese government decided to introduce several energy policy instruments to promote energy efficiency. However, energy intensity is not an accurate proxy for energy efficiency because changes of energy intensity are a function of changes in several socioeconomic factors. Chapter 6 develops an energy aggregate demand model for Chinese provinces. By employing the stochastic frontier analysis approach, the level of "underlying energy efficiency" in Chinese provinces is estimated. The advantage of the model presented in the paper is the possibility to take into account the presence of unobserved heterogeneity, and to distinguish persistent (time-invariant) from transient (time-varying) inefficiency. This analysis shows that energy intensity cannot accurately measure the level of efficiency in the use of energy in the Chinese provinces.

Chapter 7 first uses data envelopment analysis approach to estimate the operational efficiency for the Chinese provincial power sector, to provide information about the individual provincial power sectors' performance. Nevertheless, changes in efficiency can only reflect the development of performance of individual provinces and cannot account for the degree of effectiveness of the energy policies across provinces. Hence, the second part of this chapter explores the cross-province disparities in electricity generation performance by employing convergence models. The result shows that Chinese provincial power sectors converge faster to their own operational efficiency long-run growth paths than to a common one. This analysis also finds evidence that reform of pricing system, unity of the grid distribution network, urbanization, economic structural change, and avoidance of government intervention, are necessary to increase efficiency.

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Keywords: Energy Policy; Endogenous Growth; Energy Efficiency; Energy Economic Modeling; Knowledge Spillover; Convergence.

Zusammenfassung

Ökonomische Modelle sind ein wichtiges Werkzeug zur Evaluierung von potentiellen Effekten vorgeschlagener Energiepolitiken auf unsere Volkswirtschaft. Die Nutzung von Modellen und Szenarien zum Politikdesign ist in den letzten Dekaden stark gewachsen. Heute nutzen viele nationale Regierungen und internationale Institutionen die Ergebnisse der ökonomischen Politikmodellierung. Diese Modelle bieten den verantwortlichen Politikern ein effektives Verständnis der potentiellen ökonomischen Kosten und Nutzen von Strategien zur Vermeidung von Kohlendioxidemissioen. Fundierte Modellresultate helfen den Entscheidungsträger die Effektivität der Energie- und Klimapolitiken zu maximieren.

Ökonomisches Wachstum wird angetrieben durch die Akkumulation von Kapital. In endogenen Wachstumsmodellen wird technologischer Fortschritt als eine Form von Kapital betrachtet, welches durch Forschung und Entwicklung (F&E) sowie andere wissenserschaffende Prozesse akkumuliert wird. Diese Art von Modellen erlaubt eine Analyse der langfristigen ökonomischen Wachstumseffekte von Energiepolitiken. Darüber hinaus ist die technologische Entwicklung ein wichtiger Aspekt der Energie- und Klimapolitik, die man über den Kapitalakkumlationsprozess betrachten kann. Der erste Teil dieser Dissertation entwickelt einen makroökonomischen Modellrahmen um die Wachstumseffekte von Energiepolitiken in der regionalen Volkswirtschaft zu analysieren.

Kapitel 2 erweitert den Energiesektor des Landes sowohl um mehrere Sektoren als auch um verschiedene Stromerzeugungstechnologien und fossile Energiequellen. Des Weiteren wird ein endogenes Wachstumsmodell eingeführt. Dieses neue Energiemodell präsentiert vielfältige technologische Details in Form einer bottom-up Modellierung des Energiesektors. Es vermeidet jedoch einige der rechnerischen Komplexitäten die bei der Lösung zweier verbundener Modelle auftreten. Mit Hilfe dieses vereinfachten bottom-up Modells analysiert Kapitel 2 die Effekte eines Schweizer Atomausstiegs. Das Modell zeigt, dass die Volkswirtschaft eine solch ambitionierte Energiepolitik durch ausreichende Innovationen verkraften kann. Kapitel 3 verwendet dasselbe Modell für eine weiterführende Diskussion der entscheidenden Elemente einer makroökonomischen Modellanalyse. Der Hauptfokus liegt dabei auf der Problematik der Verteilungsprinzipien zwischen heutigen und zukünfitgen Generationen.

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Aus angewandter makroökonomischer Perspektive erscheint es als vielversprechend, den dynamischen Einfluss und die Größe des Effekts einer Restriktion der Input-Faktoren in einer schnell wachsenden Volkswirtschaft zu betrachten. Von einem theoretischen als auch numerischen Aspekt her ist es jedoch herausfordernd, ein komplett endogenes Wachstumsmodell zu entwicklen. Kapitel 4 zeigt, wie ein solches dynamisches Modell entwickelt und an China angepasst werden könnte. Der Modellrahmen berücksichtigt disaggregierte Industrie- und Energiesektoren, endogene Innovation und sektorspezifische Investitionen. In einer langfristigen Betrachtung bis 2050 zeigt sich, dass die Wohlfahrtskosten der Emissionsreduktionen für China zwischen 3 und 8 Prozent liegen. Die Kosten können durch eine schnellere Energietechnologieentwicklung, verstärkte Anreize zur Innovation und steigende Energiepreise signifikant reduziert werden. Darüber hinaus wird die verstärkte Urbanisierung die Kosten der Kohlenstoffpolitiken aufgrund von veränderten Konsumverhalten erhöhen.

Auf der globalen Ebene wird ein geleiteter internationaler Technologietransfer für die Berechnung der Effekte von globalen Energiepolitiken zunehmend wichtiger. Energiepolitiken könnten eine zusätzliche Schaffung von Wissen sowie einen Wissenstransfer kreieren, um die negativen Kosten höherer Energiepreise auszugleichen. Daher präsentiert Kapitel 5 ein multiregionales, multisektorales endogenes Wachstumsmodel, welches in dem Kontext die internationale Diffusion von Wissen berücksichtigt. Dieses Kapitel ermöglicht eine detaillierte Analyse der Einflüsse globaler Klimapolitiken auf Wissen und Wachstum.

Der letzte Teil dieser Dissertation besteht aus zwei empirischen Aufsätzen. Während makroökonomische Modelle sich anbieten, um die potentiellen Kosten von Energiepolitiken zu berechnen, sind ökonometrische Modelle bevorzugt, wenn es um die Schätzung der Effekte bereits implementierter Energiepolitiken geht. Die chinesische Regierung hat zur Verbesserung der Energieeffizienz vor einigen Jahren entschieden, verschiedene Energiepolitikinstrumente einzuführen. Jedoch ist die Energieintensität nicht ein passendes Proxy für die Energieeffizienz, weil die Änderungen der Energieintensität eine Funktion verschiedener sozio-ökonomischer Faktoren ist. Kapitel 6 entwickelt ein aggregiertes Energienachfragemodel der chinesischen Provinzen. Die Methode der stochastischen Frontieranalyse ermöglicht die Schätzung der unbeobachteten Energieeffizienz der chinesischen Provinzen. Der Vorteil dieser Methode ist die Möglichkeit zur Berücksichtigung unbeobachteter Heterogenitäten, um zwischen persistenter (zeitinvarianter) und transienter (zeitvarianter) Ineffizienz zu unterscheiden. Die Analyse zeigt, dass die Kennzahl der Energieintensität nicht in der Lage ist, die Energieffizenz der chinesischen Provinzen genau zu messen.

Kapitel 7 verwendet die "data envelopment" Analyse, um die Effizienz des Stromerzeugungssektors der chinesischen Provinzen zu schätzen. Veränderungen in der Effizienz des Stromerzeugungssektors per se berücksichtigen jedoch nicht die Effektivität einer überregionalen Energiepolitik. Daher erforscht der zweite Teil des Kapitels die regionalen

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Unterschiede der Effizienz der Stromerzeugungstechnologien anhand der Verwendung von Konvergenzmodellen. Das Ergebnis zeigt, dass der Energiesektor in den einzelnen chinesischen Provinzen schneller auf einen eigenen langfristigen Wachstumspfad konvergiert als auf einen gemeinsamen überregionalen Wachstumspfad. Die Analyse findet darüber hinaus Hinweise, dass eine Reform des Preissystems, die Art des Übertragungsnetzes, eine erhöhte Urbanisierung, Strukturreformen, sowie die Reduktion von Staatsinterventionen notwendig sind, um die Effizienz zu erhöhen.

Schulüsselwörter: Energiepolitik, endogener Wachstums, Energieeffizienz, energieökonomische Modellierung, Wissensexternalitäten, Konvergenz.

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1 Introduction

Energy plays a vital role in economic and social development. The analysis of energy issues and policy options is therefore a vital area of study. One of the earliest contributions concerning energy issue dates back to the book *The Coal Question* (1865), where the author W. S. Jevons expressed his concerns on the depletion of coal resources. Later on, H. Hotelling (1931) derived a price path for optimal extraction of exhaustible resources, known as Hotelling's rule. Energy economics has been actively presented in economic literature since then, particularly after the oil crisis in 1970s. Recent focus in this field includes issues such as climate change and climate policy, energy and environmental policy, demand forecasting, energy and economic growth, etc. As an applied discipline of economics, it builds a strong link to the three major topics of economics: macroeconomics, microeconomics, and econometrics. Since it is such a broad scientific subject area, a diversity of issues and methods have been applied to this field. This thesis contributes to the literature in three areas: energy and economic growth, energy policy analysis, and energy economic modeling. Each chapter relates to one or more of the three areas.

1.1 Energy and economic growth

Energy is an essential factor of production (Stern 1997). However, mainstream neoclassical economic approach treats the quantity of energy available to the economy in any period as endogenous, which leads to a downplaying of the role of energy as a driver of economic growth and production. Economists, particularly ecological economists argue that energy is used for the production of intermediate resource inputs. Hence, the rising energy price represents the increased scarcity of resources. Nowadays, resources including energy are considered as one of the essential inputs for economic development. In the literature on growth and resources, the central question is what conditions permit continuing growth, or to stay "sustainability". Technical and institutional conditions determine whether or not sustainability is possible. Technical conditions refer to things such as the mix of renewable and non-renewable resources and the substitution between inputs. This

implies technical change can lead to two types of substitution: the substitution between energy resource and other substitutes, and the substitution between different types of energies. The institutional setting includes the markets structure, the property rights, the distributional principle between today and future generations. This thesis focuses on the technical conditions which sustain the growth in the long run for an economy under restricted energy use, while part of the institutional conditions is addressed to some extent.[1]

1.1.1 Energy and capital

Economic growth is driven by the accumulation of capital stocks. In endogenous growth models, technological knowledge is treated as a form of capital, accumulated through research and development (R&D) and other knowledge creating processes. The positive externalities of technical progress compensate the diminishing returns to capital. There are also beneficial spillovers of knowledge to the economy from the R&D process so that the social benefits of innovation exceed the cost paid by the original innovators. These externalities create momentum for the sustained growth. When taking resources into consideration, one source of technical change is that depleted resources (especially non-renewable energies) can be replace by more abundant substitutes, for instance, physical capital (machines, factories, etc) and knowledge capital (plans, blueprints, etc).

The elasticity of substitution (σ) between energy and capital is a critical technical term that indicates by how much of one input to be increased to maintain the same level of output when reducing the use of the other one. A large σ implies the more possibilities of substitution. A lower value for σ suggests limited substitution can take place. In particular, if σ is less than one, energy is "essential". Solow (1974) has explicitly derived the case of σ greater than unity, where the substitution possibilities are so large that sustainability is not an issue for the economy. For the case of poor input substitution ($\sigma < 1$), Bretschger and Smulders (2012) derive from a theoretical model that growth can not be prevented with increasing energy prices (scarcities) in a multi-sector economy.

With the increasing energy price, the attractiveness of energy input in production declines. The economy should devote more resources and capital for innovation to maintain the level of production. The R&D activities create new knowledge, which is added up to the existing stock. The process of innovation exhibits an increasing returns to scale as all the old knowledge are stored and reused when necessary. Romer (1990) explains the so-called expansion-in-varieties mechanism to illustrate the endogenous growth of the economy. Actually, the increasing returns of knowledge capital represent the intertemporal knowledge spillover, which captures the positive externalities of knowledge to be used by future researchers. This is one of the main growth engines described in the next four

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[1]Chapter 3 and 4 discuss how the intertemporal discount rate affects the cost of energy policy and the economic growth.

chapters.

Additionally, the hypothesis of induced innovation says that an increase of the price of a specific factor is a spur to innovation increasing productivity via price-induced technical progress. The seminal empirical contribution of Popp (2002) finds strong evidence for induced innovation related to energy use. Jorgenson et al. (2013, p. 481) state that "there is massive empirical evidence of price-induced energy conservation in response to higher world energy prices beginning in 1973". Hence, in Chapter 4, a new channel for the price induced innovation is constructed to identify the massive and fast innovation happened in China.

Knowledge capital can also be accumulated from other sectors or regions. In open economies, the transboundary exchange of capital has to be considered. Knowledge flow in the global scale has some features, making it decisive in determining the long-run development of an economy. First, international transmission of knowledge is inexpensive and not bounded to market operations. Second, marginal returns are often assumed to be constant for knowledge but decreasing for physical capital. Many studies (Coe and Helpman, 1995; Coe et al. 1997; Keller, 1998, 2004; Lumengan-Neso et al. 2005, etc) have examined the international knowledge spillovers from the perspectives of the transmission channels and factors affecting the size of the spillovers. These types of knowledge spillovers differ from the intertemporal knowledge spillover in several aspects. The spillovers stem from the knowledge developed by outsiders. It requires time and other resources to absorb and utilize these external knowledge. Furthermore, they are prone to be exposed to external policy shocks. Change in trade treaties, new regulation on intellectual property rights, and other barriers on technology transfer will strongly impact the spillover intensity. To distinguish with intertemporal knowledge spillover, spillovers from external knowledge are named as contemporaneous spillovers. Chapter 5 includes explicitly both intertemporal and contemporaneous spillovers in a multi-region multi-sector general equilibrium framework.

1.1.2 Clean and dirty energy

With the concerns of environment and climate change, various types of energies fall into two categories: clean (renewable) and dirty (non-renewable) energy. Clean or green energy refers to renewable energy such as hydro, nuclear, solar, wind, etc, as the consumption of these energies emits no greenhouse gases. The most pressing environmental problems and resource constraints have imposed hope on technological breakthrough of clean technologies. In recent years, in a strategy of "green growth", developed countries have been rapidly developing "green" technology. The most important drivers of green technology growth are various measures of public policy, as well as new opportunities to businesses in the environmental market that is growing rapidly under the influence of consumer demand.

One exception is nuclear energy. In past decades, nuclear energy has contributed a considerable share to total electricity generation, notably in Europe, the U.S. , Japan and South Korea. Also, emerging economies like China and India are planning to increase nuclear (IAEA 2011, Table 1). However, the Fukushima nuclear accident in Japan has refueled the discussion of the potential risk of nuclear energy. The vulnerability of nuclear power plants and the economic consequences of an accident lead to a reconsideration the use of nuclear energy. Higher security standards have raised the investment and infrastructure costs, as well as the extra costs for the maintenance. The result of these considerations is that several countries have decided to shut down their nuclear power plants completely, including Germany and Switzerland.

Dirty energy includes traditional fossil fuels such as coal, oil, and gas. As these energies produce emissions, any economies taking the strategy of "green growth" should limit the use of dirty energy, or develop technologies to capture the emissions from the source. Developing countries possess high demand for climate-friendly energies and technologies, however, face barriers to access to these new technologies due to trade policies and intellectual property rights. Instead, technologies to improve the efficiency and productivity are favored by these countries. China is now the world's largest energy consumer and greenhouse gas emitter due to the highly dependence on coal. China uses around 50% of global coal consumption. However, China has emerged as the world's leading builder of more efficient, less polluting coal power plants, mastering the technologies and driving down the cost. In the meantime, China runs one of the largest numbers of Carbon Capture and Storage (CCS) pilot projects in the world.

No matter which type of energy or technology is developed, the policy orientation should be towards a way to the low-carbon economy with sustainable growth. Particularly for developing and under-developed countries, they set the economic development and poverty eradication as their first priority. Hence, the strategy of developing a low carbon economy can only be accepted if the policy of emission reduction does not hurt the growth of the economy. However, climate change is moving so fast than the effects to address it. It is clear that as the central to sustainable development, emission control will soon become an issue for developing countries in order to meet their growing needs.

Even for developed countries, currently monopolized by the political debate for solutions to global economic crisis, the room left for energy policies to combat or adapt to climate change is small. However, addressing climate change can stimulate the economy by creating new jobs and paving the road to recovery. As stated in Greenpeace's Energy Revolution, "with only 1% of global GDP invested in renewable energy by 2050, 12 million jobs would be created in the renewable sector alone; and the fuel costs savings would cover the additional investment two times over."

In this thesis, the evolution of the energy mix is captured through the substitution between different energy sources. Three fossil energies are differentiated by their respective carbon

content. Moreover, Chapter 2 and 3 extend the multi-sector endogenous growth general equilibrium model (Bretschger et al., 2011) with a detailed description of seven electricity generation technologies. In particularly, these two papers study the economic cost of energy transition towards renewable energies under the government pre-defined market share target. The results reflect the capability of an innovative economy to adapt to radical exogenous change in its energy mix. In Chapter 4, the substitution between electricity and fossil fuels is endogenous, induced by price effects. As electricity generation in China is still carbon intensive, the study introduces the development of "green technologies" which will lower the carbon content embedded in energy use.

1.1.3 The energy-growth nexus

How can an economy grow steadily when taking measures to halt climate change and tackle the current economic crisis at the same time? We first need a clear picture on the relationship between energy use and economic growth. The causal relationship between energy consumption and economic growth is one of the central questions confronts researchers in the field of energy economics, and has been investigated extensively in literature. However, there is no a general consensus about the causality between energy consumption and economic growth. For example, Yuan et al. (2007) find that there is only unidirectional causality from electricity use to real GDP but not the vice versa. In contrary, Zhang and Cheng (2009) conclude that there exists the unidirectional Granger causality running from GDP to energy consumption. Hence, such debate continues in both academic and political fields. As summarized by Ozturk (2010), the literature produces conflicting results and hence he suggests researchers should focus more on the new approaches and perspectives to get more reliable results and provide policy implications for practice. One way of avoiding the causal relationship is to formulate energy consumption and economic growth in a general equilibrium framework, which also allows for an integrated analysis of inter-sectoral linkage, particular positive externalities and spillover effects through endogenous growth mechanism. It provides an analytic framework to scrutinize many possible channels which can affect energy and growth interactively.

This thesis takes Switzerland as an example for developed countries and China as a representation for developing countries, studying the interplay of energy use and economic growth within a general equilibrium framework. Chapter 2 and 3 study how Switzerland, as an innovative economy, accommodates to stringent emission reduction and transition to renewable energies. The results highlight that innovative economies have the potential and the capacities to achieve ambitious targets in the electricity sector, and that a reform towards an electricity generation sector dominated by new renewables is economically feasible.

In Chapter 4, the effects of emission cut on economic growth for an emerging economy

are addressed through a series of scenarios considering the distinctive features of economy under the phase of transition and development. The estimation results show that it is significantly easier for a growing economy to achieve stringent emission intensity reduction targets than absolute emission cuts. It also shows that even taking into account the ability of an economy to innovate and invest according to changing energy market conditions, costs of carbon policies cannot be disregarded when the reference growth rate is high. Of course, accelerated technology development in the energy sector, intensified learning effects, and increasing energy scarcities alleviate the costs of the climate policies.

1.2 Energy policy

Energy policy deals with issues of energy development within a well defined entity, usually the national (or central) government. Measures to be used for a national energy policy include legislation (laws, treaties, directives, regulations, etc.), fiscal policies, campaigns, other energy-related research and development policy command.

1.2.1 Policy measures

There are many factors to be contained in a national energy policy. Coupled with concerns on climate change, the focus of current energy policy in the world involves two aspects: the cut of greenhouse gases, and the transition to clean energy. Hence, the national energy policy can be oriented in three directions.

Firstly, carbon tax is one of the most used instruments to control for the rise in emissions. Switzerland is one of the few participating countries that have fulfilled the Kyoto Protocol commitment for the first period between 2008 and 2012. One measure of the Swiss government is the implementation of a carbon tax. As the second commitment period 2013-2020, Switzerland declares a more stringent greenhouse gases emission reduction. This ambitious target will be attained through measures such as steeper carbon taxes. As announced the country has decided to increase the carbon tax from CHF 36 to CHF 60 per ton of CO2 from 2014. Further rise in carbon tax is also being considered according to the Swiss environment ministry, who said the tax would jump to CHF 84 ($94.25) per tonne of CO2 in 2016, from CHF 60 currently, if power-related emissions are reduced by less than 22 per cent below 1990 levels by the end of this year. The Swiss case of using carbon tax to control for emission has been discussed in Chapter 2 and 3. In China, the government is also considering the possibility of imposing a tax on emissions. Besides, a pilot project on national carbon trading scheme has been initiated in several cities in China. With environmental policy at the top of its agenda, the Chinese central government plans to establish the national wide trading market framework by 2016. Hence, in Chapter 4, the paper studies China's climate policy by introducing carbon permit pricing system. The emission reduction in the multi-region model is also

associated with increasing carbon permit price in Chapter 5.

The second measure is the introduction of renewable energies. The EU's 20-20-20 strategy highlights the significance of renewable energy in fighting for carbon emissions. Renewable energy also takes up an important part of Swiss energy mix. Almost 90% of Swiss electricity generation comes from hydro and nuclear energy. Renewable energies for electricity generation have been subsidized in Switzerland. Further money is also provided from 2013 to support the development of renewable energies[2]. A specific goal for renewables is also set out in China's 12th Five Year Plan, which specifies values of 11.4% for total primary energy from non-fossil sources by 2015 and 15 percent by 2020. 20% of current electricity generation is attributed to renewable resources, 18% stems from hydropower. Chapter 2 and 3 explicitly model the development of renewable energies as various electricity generation technologies are characterized by varied production cost. Chapter 4 introduces the impact of renewable energy in China with declining carbon content embedded in the consumption of energies.

Finally, measures on the improvement of energy efficiency are useful in reducing the use of fossil energy and thus cutting emissions. Energy efficiency is a vital component of a sound energy strategy. IEA decided to put energy efficiency in the focus of its special energy resource analysis for the first time in its latest version of the World Energy Outlook. Energy efficiency is one priority of Swiss "Energy Strategy 2050". One of the main tasks for the China's 12th Five-Year plan period is to improve the level of energy efficiency. However, the barrier to report energy efficiency is obvious. There are many behavioral and structural factors that can affect the energy efficiency. Quite often the terms energy intensity and energy efficiency are used inter-changeably. But, energy intensity is not a good estimation to approximate energy efficiency accurately since many other factors can largely influence the efficiency of energy use (Filippini and Hunt, 2011, 2012). Hence, the Chinese government introduced a new term "carbon intensity" (carbon emission per unit of GDP) to define the energy and climate policy target. It says that carbon intensity will be reduced by 17% by the end of 2015 compard to 2010 level. Again carbon intensity can be problematic as energy intensity when used as a proxy for energy efficiency. China is not the only one of its kind that failures to report energy efficiency. EIA keeps on using energy intensity as an indicator of energy even though it realizes the importance of energy efficiency for the nation's energy strategy (EIA 1995). In Chapter 6, an econometric modeling approach is developed to identify the underlying energy efficiency levels for Chinese provinces. Chapter 7 employs an alternative method in estimating the efficiency levels of Chinese provincial power sectors. These two studies provide concrete examples on the efficiency analysis.

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[2]From 2013, an annual maximum amount of 500 million francs will be made available, funded via an extra charge on each kilowatt hour of electricity consumed.

1.2.2 Policy levels

National energy policy has its instinct to secure energy supply for domestic demand, but it also impacts the policies in foreign countries, particularly neighbor countries. As the inception of climate change, the energy policies to deal with global warming have been intensively discussed in both national and international level. People are increasingly aware of the necessity of building up a global framework in order to achieve the stabilization of the carbon content level in the atmosphere.

To fight for the climate change, most industrialized economies committed to reduce emissions under an international agreement, the so-called "Kyoto Protocol". As the first commitment period ended in 2012, these developed economies start to reconsider the future policies for the emission reduction. Worldwide, the United Nations Framework Convention on Climate Change (UNFCCC) is taking on the role of achieving an international climate agreement such that all participating economies share the burden of cutting emissions and eventually "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Besides, The Asia-Pacific Partnership on Clean Development and Climate (APP) is creating a framework for international cooperation to facilitate the transfer of clean and efficient technologies among the partners to meet pollution reduction, energy security and climate change concerns. In Europe, policy makers introduced a set of binding legislation which aims to ensure the EU meets its ambitious climate and energy targets for 2020, which is known as the European "20-20-20" Targets. These targets set three key objectives for 2020: (1) to have a 20% (or even 30%) reduction in CO2 emissions compared to 1990 levels, (2) 20% of the energy, on the basis of consumption, coming from renewables and (3) a 20% improvement in the EU's energy efficiency. The Global Climate Change Alliance, launched by the European Commission, deepens the policy dialog between the EU and developing countries and steps up support to implement mitigation measures for both regions. The purpose of Chapter 5 is to construct an analytical workhorse featuring the global interplay of regional climate negotiation.

Within a country, regional or provincial governments and industries will also exercise various policies. These policy measures are lesser in legal status, but are still equally important to national measures. In fact, to be more efficiently administer certain activities, it is necessary to set up provincial and municipal regulations. For example, each of the provinces in China has its own building code for the purpose of monitoring energy conservation practices, along with the national wide building code. In industry level, the regulation on energy saving is also differentiated and revised according to the production process and work environment.

There are many studies in literature which have investigated the effects of the energy policies in regional level. Studies focusing on developed economies such OECD countries and the US include Zhou and Ang (2008), Filippini and Hunt (2011, 2012, 2013). Hu

and Wang (2006), Wei et al. (2009) explore the Chinese provincial data for efficiency analysis. In sectoral level, Fisher-Vanden et al. (2004) utilize the panel data for 2500 industrial enterprises. Other studies on regional or sectoral level of energy-related issues also include Romero-Avila (2008), Jobert et al. (2010), Marrero (2010), Robinson (2007), Jaunky (2008), Jiang and Wu (2008), Maza and Villaverde (2008), Zachman (2008), Liddle (2009).

In this thesis, two papers fall into this category. Chapter 6 deals with the energy efficiency policies in China's provincial level and Chapter 7 studies the convergence of operational efficiency in provincial power sector. Both papers treat each of the provinces as one individual entity for the effects of respective policies. If thinking of the whole world as one single country and the regions as subset of the country, Chapter 5 is of this framework as well since it takes the carbon emission policies in each region into account and each region is one player in the global game of international climate agreement.

1.3 Economic models for energy policy analysis

Economic models are an important tool for evaluating the potential impact of proposed energy policies on our economy, and hence to improve the usefulness of energy polices in public decision making. The use of model-based analysis and scenarios in energy policy design and assessment has been growing in the last decades. National government and inter-governmental bodies now increasingly rely on the economic modeling results for advice. Though different in assumptions and other modeling elements, the model results are often explained by the following factors represented in the model:

- The assumed baseline of the economy: how the economy behaves in the absence of energy policies;

- The way of modeling energy policies, e.g., carbon tax, emission trading, green subsidy;

- The market structure of involved industries in the economy;

- How technological change is characterized, including general technical change, specific energy price induced change, technical change due to knowledge spillover;

- The possibility of inclusion of uncertainty, damage functions as in climate models.

Economic models offer policy makers an effective understanding of the potential economic cost and benefits of mitigating carbon emissions. Sound modeling results guide decision making in energy and climate policies in a direction of maximizing the effectiveness of the mitigation effort.

In terms of modeling approach, this thesis can be separated into two parts. The first part includes four papers (Chapter 2, 3, 4, 5), where the macroeconomic model is employed for analyzing the impacts of potential (future) energy policies. The second part is composed of Chapter 6 and 7, where the econometric model is used to investigate the information contained in historical data, and identify the results of past policies for future decision making.

1.3.1 Macroeconomic model

Macroeconomic models, usually known as "top-down" models in energy-economic modeling literature, describe the economic system from aggregate economic variables by applying macroeconomic theory to real data on consumption, prices, income to model the supply and final demand for goods and services. As aggregate economic variables are generally more reliable in representing the macroeconomic relationship, it is therefore common to adopt high levels of aggregation for top-down models when they are applied to long time frames (Nakata 2004).

In the macroeconomic model framework, a broad general equilibrium feedback mechanism is addressed. The links between energy sector and other economic activities, the growth impacts of energy policies on the sectoral, national and global scale are extensively explored. However, some critics complain that aggregate macroeconomic models do not capture the technology details and complexity of supply system. Specific technologies are not directly modeled. Hence, macroeconomic models are linked with energy sector models to avoid the limitations. This is the so-called "hybrid modeling". Hybrid model combines methods, assumptions between models in order to avoid certain limitations in a single model system.

Bretschger et al. (2011) describe an endogenous growth model with multi-sector for the Swiss economy. This thesis further extends the model to capture various electricity generation technologies and fossil energy sources in the energy sector. The newly extended energy model features rich technology details as in bottom-up energy sector models. However, it avoids to some extent the computational complexities involved in solving two hard-linked models. With the simplified bottom-up module, Chapter 2 studies the effects of nuclear phase-out policies in Switzerland. Chapter 3 employs the same model for further discussion on some crucial elements in macroeconomic model analysis.

1.3.2 Econometric model

If macroeconomic models are powerful in evaluating the potential cost of energy policies, econometric models are preferred in estimating the effects of energy policies which have been implemented. In particular, this thesis employs econometric models to address the energy efficiency issue.

There are already a number of technological initiatives to promote energy efficiency and pollution abatement provided by the Chinese government.[3] As summarized in Zhou et al. (2010), massive attention is devoted to energy efficiency measures with focus on the so-called "top ten priorities" and "Ten key Projects". However, there is no sound measurable approach to be used for providing informative results and controlling for projects quality. Some indicators such as energy intensity are still widely used in government policy reports.[4] A better understanding and measurement of the level of energy efficiency could improve the effectiveness of interventions done by the central government.

There are some approaches proposed in the energy economics literature regarding avoiding the problems of these simple efficiency indicators, such as Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). DEA is basically a bottom-up framework used to create energy efficiency indicators. Whereas SFA is based on the estimation of a parametric, best practice frontier for the use of energy where the level of energy efficiency is computed as the difference between the actual energy use and the predicted energy use.

Several papers in literature have studied the energy efficiency in China using DEA (e.g.: Hu and Wang, 2006; Wei et al., 2009). Chapter 6 measures the level of "underlying energy efficiency" based on SFA. The advantage of this approach in the context of measurement of energy efficiency is the possibility to take into account the presence of unobserved heterogeneity, to distinguish persistent (time-invariant) from transient (time-varying) inefficiency and to take into account the statistical noise of approximation errors and random behavior.

Chapter 7 uses DEA to compute the technical efficiency in Chinese provincial power sectors. SFA uses specific assumptions about the population distribution. If the assumptions about the distribution fail to hold, it will yield biased estimates. Instead, DEA does not account for statistical noise and can be sensitive to outliers. No assumption is made with respect to the population distribution. The data are left to speak for themselves. Moreover, SFA relies on detailed information about the institutional characteristics, cost and price information in order to adequately specify a production function (Paxton, 2003). In the case where limited data on inputs, prices and costs are available, the DEA method is preferred. This chapter then investigates the convergence using both parametric and non-parametric approaches to have a complete analysis of this issue.

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[3]See IEA website for summary of the energy efficiency related policies and measures in China. http://www.iea.org/policiesandmeasures/energyefficiency/?country=China

[4]Energy intensity is not an accurate proxy for energy efficiency because changes in energy intensity are a function of changes in several socioeconomic factors.

1.4 Outline of the thesis

As indicated, there are many energy-economics models. Each model is differentiated with others by taking into account information on technology, economic structure, policy shocks at different degrees. As the objective of the thesis is to provide models which can produce prudent results for policy goals, I focus on the models that:

- project the long-run regional and sectoral economic growth under (potentially) restricted energy uses;

- investigate the impact of "externalities" derived from innovation and knowledge diffusion on the sustainable economic development;

- provide scientific data support for future negotiation of international climate agreement;

- evaluate the factors which impacts the regional and sectoral efficiency of energy use in the past for future policy design.

This thesis is composed of 6 individual papers. The content is structured as follows. Chapter 2 discusses the economic effects of nuclear phase-out in Switzerland by employing an extended version of CITE model where the energy sectors are represented in a more detailed bottom-up fashion. We find that the nuclear phase-out can be achieved at relatively low costs, even when the expansion capacities of other technologies are limited. Consumer welfare decreases by 0.4% at the maximum compared to business as usual. Our results show that an economy can cope well with ambitious energy policies through sufficient innovation. Economic growth is not slowed down significantly. The phase-out policy contributes to a structural shift in favor of innovative, energy-extensive sectors. It does not work against the climate policy goals but rather accelerates the transition to a less energy-dependent economy.

Chapter 3 is an extension of the analysis of Chapter 2. It investigates the social cost of energy transition towards renewable energies in the future, taking Switzerland as an example. Three important and frequently debatable assumptions that may significantly affect the policy cost: the capital growth rate and the innovativeness of an economy, as well as the intertemporal discount rate, are extensively studied. By incorporating new results from recent empirical studies, this study shows that the energy transition can be achieved with relatively small welfare loss. However, future investment environment can impact the sectoral growth differently, leading to significant change of the economic structure. The discounting rate has only mild effects on sectoral growth in a dynamic setting. In the sectoral level, knowledge intensive sectors suffer drastically if the economy is less innovative and lower innovation can result in negative effects on substituting fossil energies.

Chapter 4 investigates the Chinese energy policies by constructing a model tailored for an emerging economy. There is widespread concern that an international agreement on stringent climate policies will not be reached because it would imply too high costs for fast growing economies like China. To quantify these costs we develop a general equilibrium model with fully endogenous growth. The framework includes disaggregated industrial and energy sectors, endogenous innovation, and sector-specific investments. We find that the implementation of Chinese government carbon policies until 2020 causes a welfare reduction of 0.3 percent. For the long run up to 2050 we show that welfare costs of internationally coordinated emission reduction targets lie between 3 and 8 percent. Assuming faster energy technology development, stronger induced innovation, and rising energy prices in the reference case reduces welfare losses significantly. We argue that increased urbanization raises the costs of carbon policies due to altered consumption patterns.

Chapter 5 constructs a global general equilibrium model with multi-regions and multi-sectors. In each of the region and sector, the model features increasing returns to scale through the endogenous growth mechanism developed by Romer (1990), as well as contemporaneous knowledge spillovers from other sectors and regions. Capturing the regional linkage, with knowledge diffusion as one important element for sustainable growth, is crucial for a precise estimation of policy impacts. This paper enables a detailed study of the impacts of global climate policy on knowledge and growth.

Chapter 6 proposes an aggregate energy demand model for Chinese provinces. China is one of the largest consumers of energy globally. The country also emits some of the highest levels of CO2 globally. The growth rate of energy consumption in China is about 6% per year and it consumed 21% of the world's total energy in 2012. In recent years, the Chinese government decided to introduce several energy policy instruments to promote energy efficiency. For instance, reduction targets for the level of energy intensity have been defined for provinces in China. However, energy intensity is not an accurate proxy for energy efficiency because changes in energy intensity are a function of changes in several socioeconomic factors. For this reason, in this paper we present an empirical analysis on the measurement of the persistent and transient "underlying energy efficiency" of Chinese provinces. For this purpose, a log-log aggregate energy demand frontier model is estimated by employing data on 29 provinces observed over the period 2003 to 2012. Several econometric model specifications for panel data are used: the random effects model and the true random effects model along with other versions of these models. Our analysis shows that energy intensity cannot measure accurately the level of efficiency in the use of energy in Chinese provinces. Further, our empirical analysis shows that the average value of the persistent "underlying energy efficiency" is around 0.81 whereas the average value of the transient "underlying energy efficiency" is approximately 0.97.

Chapter 7 employs several econometric techniques for the assessment of efficiency convergence. To analyze the operational efficiency of Chinese power sector at the provincial

level, this paper studies the convergence of technical efficiency and productivity growth of electricity across 29 Chinese provinces during the period 1996-2008 using several convergence models. Depending on the model being employed, we find evidence of convergence of operational efficiency towards either a national steady state or towards their own steady states, with the latter process occurring more rapidly. In essence, our study provides evidence of negative effects of government intervention. Additionally, we use the nonparametric distribution dynamics approach to analyze intra-distributional dynamics of technical efficiency and productivity. We find some support for productivity convergence while technical efficiency does not converge for provinces with relatively low levels. We discuss policy implementations based on our model results and highlight several aspects for policy making in the power sector reforms currently being undertaken.

2 Economic effects of nuclear phase-out policy: A CGE analysis [1]

2.1 Introduction

In past decades, nuclear energy has contributed a considerable share to total electricity generation, notably in Europe, the U.S. , Japan and South Korea. In 2010, 19 European countries had at least one nuclear power plant in operation and many relied substantially on nuclear energy, like the UK (nuclear share 15.7%), Germany (28.4%), Switzerland (38.0%) or France (74.1%). Also, emerging economies like China and India are planning to increase nuclear (IAEA 2011, Table 1). In 2011, the IEA projected that "the share of nuclear in global primary energy supply increases from 6% in 2008 to 7% in 2035" (IEA 2011, p.20).

However, the attractiveness of nuclear energy has decreased significantly with the recent catastrophic nuclear accident in Fukushima, highlighting the vulnerability of nuclear power plants and the economic consequences of an accident. This event has refueled the discussions on the external costs of nuclear energy and led to considerable tightening of security standards. Higher security standards and input prices have raised investment and infrastructure costs for new reactors.[2] Moreover, the problem of how and where to store nuclear waste is still unsolved. As a consequence, nuclear energy is increasingly viewed as a problematic technology for energy generation, which has led several countries to reconsider their electricity mix. Recently, Germany and Switzerland have decided to phase-out nuclear completely. Considering the shares of nuclear energy in these two countries and the envisaged time frames for the phase-out,[3] it entails major changes in the involved economies. The scope of possible consequences includes rising energy prices due to reduced supply, a switch to more expensive energy sources[4], a higher dependence

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[1]This chapter represents the joint work with Lucas Bretschger and Roger Ramer.
[2]Examples are the Olkiluoto plant in Finland and the Flamanville plant in France.
[3]Germany plans to shut down the last plant in 2022, Switzerland in 2034.
[4]See Nestle (2012) for a recent discussion of these issues.

on foreign energy, or a possible conflict with climate targets if nuclear is replaced by gas or coal fired plants[5]. On the positive side, increased innovation and higher investments in renewable energy sources and technologies, which are induced by nuclear phase-out, could not only help to reduce energy demand but also bring about general growth impacts in the medium and long run.

In this paper, we analyze the economic consequences of a gradual nuclear power phase-out policy, using the example of Switzerland. Given the relatively high share of nuclear energy, the limited potential for additional hydropower and the political aim not to increase foreign dependency, the Swiss policy can be viewed as an ambitious and challenging project with effects on many levels of the economy. Looking at the relevant long-run impact, we are particularly interested in the induced innovation effects (both on the sectoral and on the aggregate level) and the structural changes in the economy. We apply a model especially designed for that purpose, the Computable Induced Technical change and Energy (CITE) model, see Bretschger, Ramer and Schwark (2011), which is a CGE model with fully endogenous growth. For the present study, the original CITE model has been extended with a bottom-up model to include a broad range of different technologies in the electricity sector. This enables us to explicitly show the effects and requirements on the technological level and the underlying substitution potentials.

Several papers have studied the costs and the economic impacts of nuclear phase-out policies in general equilibrium frameworks. Nordhaus (1995), Andersson and Haden (1997) and Nystrom and Wene (1999) investigated the case of Sweden[6], Hoster (1998), Welsch (1998), Welsch and Ochsen (2001), and Boehringer, Hoffmann and Voegele (2002) provide analysis for Germany. The costs of the phase-out policies depend on the number of available substitutes (and hence the degree of detail of the energy sector) and their capabilities, on the regulation scheme of the phase-out, and on the limitations imposed on carbon emissions. If no limit is imposed on the use of fossil fuels as a replacement for nuclear energy, a phase-out tends to raise carbon emissions substantially (see also Nakata (2002) and his study on Japan). Boehringer, Wickart and Mueller (2001) investigate the economic impacts of two policy proposals that aimed at restricting the use of nuclear energy in Switzerland. They find non-negligible phase-out costs for the more stringent case, mainly because this proposal administered the use of non-competitive sources as substitutes[7]. Bauer et al. (2012) study nuclear and climate policy from the global

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[5]van der Zwaan (2002) provides a detailed discussion of this issue. He shows that a significant expansion of nuclear energy could greatly contribute to a reduction of global emissions. However, he also shows that these benefits could easily be outweighed by the corresponding increases in nuclear waste, security issues and increased proliferation.

[6]Following the nuclear accident in the US power plant Three Mile Island 2 in 1979, the Swedish government decided to phase out nuclear energy until the year 2000. Later on, this deadline was moved to 2010, and in 2009, the phase-out plans were completely abandoned. Today, nuclear energy still has a share of about 38% on total electricity production in Sweden.

[7]The two proposals were "Strom ohne Atom" ("electricity without nuclear energy") and "Moratorium plus". The former postulated a limitation of the operational lifetime of powerplants to 20-30 years, and nuclear energy was requested to be replaced with combined heat and power. The latter was less restrictive

perspective concluding that the nuclear phase-out has minor effects on macroeconomic development[8]. Marcucci and Turton (2012) use a bottom-up approach with endogenous technology learning to show that the decision to stop nuclear in Switzerland results in losses of 0.7 percent of GDP in 2030 and 0.5 percent in 2100 compared to the scenario with nuclear.[9]

Our paper differs from these contributions in several respects. First, most of these papers restrict their attention to the impacts at the technology level[10]. The focus of our investigation is on the macroeconomic consequences of the policy, which largely determine whether the policy is desirable. Second, existing studies either use pure energy system models or models where economic growth is treated as an exogenous variable. We use a CGE model with endogenous growth in all sectors. Specifically, we show how the nuclear phase-out affects long-term growth at the aggregate and at the sectoral level and how the structure of the economy changes over time. The main transmission mechanism under study are sectoral innovation and investment decisions. Finally, we combine our top-down approach of the dynamic macroeconomy with a detailed bottom-up model of the electricity sector, to exploit the technical information on future technology development in an optimal way.

We find that the phase-out can be achieved with welfare losses amounting to a maximum of 0.4% compared to a scenario where only a climate target is included. Moreover, we show that the phase-out leads to structural adjustments in favor of innovative and energy-extensive sectors. There is no conflict between climate policy targets and the phase-out policy. On the contrary, the phase-out of nuclear energy can even contribute to a greening process in the economy.

The paper is structured as follows. Section 2.2 introduces the model features and the data. Section 2.3 presents the simulated policy scenarios. The results of the simulations and associated sensitivity analysis are discussed in Section 2.4. Section 2.5 concludes.

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and limited operation time to a maximum of 40 years. Both proposals were put to vote in 2003, and they were both turned down.

[8]They use the ReMIND-R model to explicitly reflect the adjustment costs due to acceleration of capacity build-up and resource extraction. Their analysis show that the GDP loss of climate policy is 2.1% in 2050, the incremental costs of a nuclear phase-out is about 0.2% in 2050.

[9]As we do in this paper, climate policies are given in both with- and without- nuclear scenarios in their analysis.

[10]The exceptions are Welsch (1998), Welsch and Ochsen (2001) and Boehringer, Wickart and Mueller (2001). The two German studies find GDP decreases in the range of 0.01% to 0.3%, depending on the time frame of the phase out. Boehringer et al. report long-term GDP reductions between 0.01% and 0.38%. Out of these three studies, only Boehringer et al. make restrictions on carbon emissions.

2.2 The model

2.2.1 Aggregate economy

The model we use is a multi-sectoral CGE model with fully endogenous growth. Growth in the different sectors is driven by an expansion-in-varieties mechanism, based on the seminal contribution of Romer (1990). Investments in capital and knowledge extend the number of capital varieties, which foster factor productivity. A graphical representation of the nested production functions is given in the Appendix.

Production of each non-energy sector i, which we call a "regular" sector, is represented by a multi-stage nested CES-function, see Figure A.1 in the Appendix. Final sectoral output Y_i is produced under the conditions of CES production function, according to

$$Y_i = [\alpha_i Q_i^{\frac{\sigma_Y-1}{\sigma_Y}} + (1-\alpha_i)B_i^{\frac{\sigma_Y-1}{\sigma_Y}}]^{\frac{\sigma_Y}{\sigma_Y-1}}, \tag{2.1}$$

where the two inputs are the intermediate composite good, Q_i , and composite output from the other sectors, B_i; σ_Y is the elasticity of substitution between the inputs; α_i and $1-\alpha_i$ are the value shares.[11] The crucial model element is the determination of the intermediate composite good Q_i, which reads

$$Q_i = [\int_{j_i=0}^{J_i} x_{j_i}^\kappa dj_i]^{1/\kappa}, \tag{2.2}$$

with $0 < \kappa < 1$ and x_{j_i} denoting the quantity of the jth type of specialized intermediate good. J_i is the number of intermediates available in a sector at each point in time. κ reflects the substitutability between the intermediate goods and, at the same time, measures the gains from diversification, i.e. the productivity increase of the economy when using a larger variety of intermediate goods. Expression (2.2) shows that Q_i can be increased by either raising intermediate goods quantity, x_{j_i}, or an expansion in varieties, J_i, which is achieved by investments into new varieties. Taking the two points in time t and $t+1$, investments in physical capital, I_{Pi}, and non-physical investments, I_{Ni}, determine the stock of sectoral varieties in period $t+1$ according to

$$J_{i,t+1} = [\gamma_i I_{Pi,t}^{\frac{\tau-1}{\tau}} + (1-\gamma_i)I_{Ni,t}^{\frac{\tau-1}{\tau}}]^{\frac{\tau}{\tau-1}} + (1-\delta_t)J_{i,t}, \tag{2.3}$$

where τ is the elasticity of substitution between the two investment types, γ_i and $1-\gamma_i$ are the value shares, and δ_t is the depreciation rate.

Based on new growth theory, research output depends on research labor and other specific inputs used in the research labs; moreover, research efforts are supported by positive learning spillovers which are proportional to the number of already developed varieties,

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[11]The optimization programs of the different firms are presented in Bretschger, Ramer and Schwark (2011).

J_i. Accordingly, non-physical investments, I_{Ni}, are determined by labor in research, R_i, non-labor inputs in R&D, I_{Ri}, and the number of intermediate goods, J_i, according to

$$I_{Ni} = [\beta_i(\frac{J_i}{z_i} \cdot R_i)^{\frac{\omega-1}{\omega}} + (1-\beta_i)I_{Ri}^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}}, \tag{2.4}$$

with β_i and $1 - \beta_i$ labelling the share parameters, ω representing the elasticity of substitution between the inputs, and $1/z_i > 0$ denoting the spillover intensity. Total research labor, R, is assumed to be constant. It can be reallocated between sectors and its productivity in each sector increases with the factor $\frac{J_i}{z_i}$, i.e. with the number of existing varieties and with spillover intensity, reflecting the intensity of the learning effects in the research lab. By determining the decisions for research investments within the model, all the factor productivities are endogenously derived by the model equations.

For the present paper analysis, we aim at representing the Swiss energy mix in great detail. Notably, we use a detailed bottom-up approach for the cost functions of the different technologies. We include seven different technologies that are available to produce electricity. The bottom-up model of the electricity sector is then combined with the macroeconomic top-down part.

2.2.2 The energy sector

The optimization problems for energy suppliers are presented in the form of cost minimization, which is the dual-form problem of usual profit maximization. Assuming perfect competition, in the optimum the market price equals marginal costs. Accordingly, the following price equations fully reflect the underlying cost and production functions. We use P to denote prices in general and assume that both consumers and producers use an energy aggregate consisting of electricity and fossil energy. In Switzerland, electricity is mainly generated by carbon-free technologies, so electricity and fossil energy are strictly differentiated in the model[12]. The market price P_{egy} of energy aggregate is given by:

$$P_{egy} = \left[\alpha P_{ele}^{1-\sigma_{egy}} + (1-\alpha)P_{fos}^{1-\sigma_{egy}}\right]^{\frac{1}{1-\sigma_{egy}}}, \tag{2.5}$$

where P_{ele} is the price of total electricity (produced in the electricity sector) and P_{fos} the price of total fossil energy. α is a share parameter and σ_{egy} denotes the elasticity of substitution between electricity and fossil energy. The variance of values for σ_{egy} used in the literature is large, ranging from poor substitutability, see e.g. Goulder and Schneider (1999), to values considerably above unity, see Gerlagh and van der Zwaan (2003) or Acemoglu et al. (2012). Given the long time horizon of our study (38 years), we consider the assumption of good substitutability to be the relevant case for our analysis. We

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[12]This assumption is also valid for countries where renewable technologies are highly appreciated, for example in Sweden the use of fossil energy for electricity generation is extremely small, taking up less than 3% of total production.

therefore use a value of 1.5 as a main calibration value but test deviations from this assumption in the sensitivity analysis.

The electricity sector includes two activities: electricity generation on the one hand and electricity transmission and distribution on the other. They trade off according to:

$$P_{ele} = \left[\mu P_{gen}^{1-\sigma_{ele}} + (1-\mu)P_{dist}^{1-\sigma_{ele}}\right]^{\frac{1}{1-\sigma_{ele}}}, \tag{2.6}$$

with μ as share parameter and P_{gen} and P_{dist} denoting prices of total electricity generation and electricity transmission and distribution, respectively. The used energy input-output table captures electricity transmission and distribution as one single sector independent of fuel choices. Hence we assume that electricity generated from all sources are dispatched through this unique grids network. The underlying production function assumes that there is a substitutability (denoted by σ_{ele}) between the generation and the distribution of electricity. The literature typically assumes low values for σ_{ele}, ranging from perfect complementarity (Rausch and Lanz 2011) to 0.7 with a possibility to substitute (Sue Wing *et al.* 2011). Sue Wing (2006) assumes that the elasticity of substitution between these two activities is 0.5. We follow this assumption and set σ_{ele} equal to 0.5. The subsector *dist* produces infrastructure to transmit and distribute electricity. We assume the same production structure for *dist* as for normal production sectors (see Figure A.1 in the Appendix).

Finally, electricity is generated using seven technologies: Hydro (*hyd*), nuclear (*nuc*), waste (*wel*), conventional thermal plants (*ctp*), solar (*sun*), wind (*win*) and biomass (*bio*). The aggregation of output from these technologies captures two features: it (i) allows for different marginal costs for technologies and (ii) represents multiple types of generation technologies that are simultaneously dispatched by assuring positive activity levels. P_{gen} denotes the price of a composite consisting of electricity produced by the seven technologies and is given by the CES formulation:

$$P_{gen} = (\sum_h \delta_h P_{y_h}^{1-\sigma_h})^{\frac{1}{1-\sigma_h}}, \tag{2.7}$$

where the subscript h denotes the active technologies; δ_h indicates the share of technology *tech* of total electricity generation ($\sum_h \delta_h = 1$). The shares in the benchmark year 2005 are listed below in Table 2.1[13]. Given the topic of the paper, the parameter σ_h plays an important role, because it determines to what degree the other technologies can substitute for nuclear energy. It must be calibrated in a way that "strikes a balance between the homogeneity of electric power as a commodity and the considerable variation in the characteristics of the technologies employed in its generation" (Sue Wing 2006, p. 3852). We assume that the individual technologies are good but not perfect substitutes

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[13]Sources for data on electricity production are the Swiss Electricity Statistics (SFOE 2006) and the Swiss Statistics of Renewable Energy (SFOE 2006) for the year 2005.

and set $\sigma_h = 10$ as in Sue Wing (2006). However, the rate of capital stock turnover in the electricity sector is relatively slow. Hence, in the sensitivity analysis we also test lower values of σ_h to capture the sunk costs associated with investments in different technologies.

Table 2.1: Electricity technologies and their production in 2005

Technology	Production in GWh	Share
Hydro	32800	56.60%
Nuclear	22020	38.00%
Conventional Thermal Plants	2100	3.62%
Waste / Sewage Plants	968	1.67%
Biomass	43	0.07%
Solar Energy / Photovoltaics	20	0.03%
Wind	9	0.01%

The endogenous determination of factor productivities, see Section 2.1, equally applies to the energy sector. In analogy to the rest of the economy, efficiency depends on three different factors (see Figure A.1 in the Appendix): (i) endogenous capital build-up and sectoral capital inflow, (ii) investments in energy research, and (iii) research labor used for developing innovations in the energy sector. When energy becomes relatively expensive compared to the other inputs, substituting for the relatively expensive input entails energy efficiency improvements. The endogenous growth mechanism of the other model sectors equally applies to the electricity sector.

Electricity generation *gen* and electricity transmission *dist* (see the second level nesting in Figure A.2 in the Appendix) are determined by a process according to the production of regular sectors (see the top level nesting in Figure A.1). The different electricity generation technologies (see lowest level in Figure A.2) compete in terms of production cost to gain mobile factors for capacity expansion.

We use information on levelized cost of different energy technologies resources (EIA 2012) to set up the individual cost functions for new renewables. Cost functions for other technologies are derived from the Energy IOT. In general, The cost functions are assumed to have the following form:

$$P_h = \sum_f (\beta_f P_f) + P_{cap,h}, \tag{2.8}$$

where P_h denotes the price of technology h, β is a share parameter, P_f the cost of production factors (labor L, capital K, and other inputs V) and $P_{cap,h}$ denotes the capacity rent of technology h, which becomes positive when the supply of this technology is restricted and demand exceeds supply. In the benchmark scenario, we assume that all technologies operate at full capacity, so that $P_{cap,h} = 0$ for all technologies. The capacity rent becomes relevant when quantity restrictions (which are exogenously given) are imposed upon technologies in the policy scenarios. Table 2.2 describes the cost

structure of different technologies.

Table 2.2: Share of factors for power generation across technologies

Technology	Labor	Other inputs	Capital
hyd	0.20	0.55	0.25
nuc	0.15	0.60	0.25
wel	0.35	0.40	0.25
ctp	0.20	0.55	0.25
sun	0.08	0.67	0.25
win	0.09	0.66	0.25
bio	0.13	0.62	0.25

Note: factor shares of *hyd, nuc, wel, ctp* are estimated from Energy IOT (Nathani *et al.* 2011); the levelized capital cost in EIA (2012) is used to estimate the capital share of new renewables (*sun, win, bio*). The capital is calibrated to 0.25 in the benchmark scenario according to Bretschger, Ramer and Schwark (2010).

The second major element of the energy sector is fossil energy. As indicated, in the Swiss case, electricity is assumed to be (almost entirely) carbon-free, with the exception of some electricity produced in conventional thermal plants. Fossil fuels are used primarily for heating and transport. This is why we strictly differentiate between electricity and fossil energy (see equation 2.5). Total fossil energy Y_{fos} is produced using three technologies: Oil (*oil*), gas (*gas*) and district heating (*dhe*). In Switzerland, district heating refers to utilization of waste heat from large energy and waste incineration plants for heating purposes. District heating is produced in central facilities and then supplied to consumers via a pipeline network in the form of hot water for heating and hot-water supply. Hence, this is one form of technology for fossil energy use. These three technologies are assumed to trade off in Cobb-Douglas fashion and the price index reads:

$$P_{fos} = P_{oil}^{\xi_{oil}} P_{gas}^{\xi_{gas}} P_{dhe}^{\xi_{dhe}}, \tag{2.9}$$

with $\xi_{oil} + \xi_{gas} + \xi_{dhe} = 1$. Gas is fully imported, but distribution requires some domestic inputs as well, which is why it is treated as a regular sector similar to the other technologies. We assume that crude oil (also fully imported) enters the production function of Y_{oil} at the top level. A graphical overview of the energy sector can be found in the Appendix (see Figure A.2).

The usage of fossil fuels produces carbon emissions. The three technologies differ in their carbon intensities (i.e. in the amount of carbon emitted per unit).[14] We assume that oil has the highest carbon intensity, followed by gas and district heat. These carbon intensities are relevant for the effective tax rates imposed on fossil fuels later on.

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[14]Carbon intensities in the model are 1.35 for *oil*, 1.01 for *gas* and 1 for *dhe*.

2.2.3 Consumers

As in the original model version, we assume that a representative, infinitely lived household allocates its factor income between consumption and investments under perfect foresight and in accordance with intertemporal utility maximization. Utility is derived from consumption according to

$$U = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t C_t^{1-\theta} \right]^{\frac{1}{1-\theta}}, \tag{2.10}$$

with ρ denoting the utility discount rate and θ denoting the intertemporal elasticity of substitution. C represents an aggregate of different goods, consisting of consumption of a regular sector output composite C_y and an energy aggregate C_e. C_y and C_e are linked as follows

$$C = \left[\zeta C_y^{\frac{\sigma_C-1}{\sigma_C}} + (1-\zeta) C_e^{\frac{\sigma_C-1}{\sigma_C}} \right]^{\frac{\sigma_C}{\sigma_C-1}}. \tag{2.11}$$

The elasticity of substitution σ_C is set to 0.5. As a new feature, we further disaggregate the energy composite C_e. It is assumed to consist of electricity consumption C_{ele} and the consumption of fossil fuels C_{fos}, as

$$C_e = \left[\phi C_{ele}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} + (1-\phi) C_{fos}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} \right]^{\frac{\sigma_{ce}}{\sigma_{ce}-1}}. \tag{2.12}$$

Like in the production part of the model, oil, gas, and heating are aggregated to fossil energy consumption, since all of them use primary fossil fuels for production and emit greenhouse gases. Moreover, as mentioned above, we distinguish energy consumption between electricity and non-electricity energies due to the fact that electricity in Switzerland is basically carbon free. The literature provides mixed estimates for the elasticity of substitution σ_{ce}. Static studies typically assume a high degree of complementarity with values between 0 (Koschel 2000) and 0.5 (Boehringer and Rutherford 2005). However, as indicated above, good substitutability with the substitution elasticity of 1.5 seems more valid for the analysis conducted here. We therefore set this value for our analysis. This implies that the compensated price elasticity of electricity demand for consumption in the long run is about -1. We also test different substitution elasticities to allow the price elasticity ranges between -0.54 (which corresponds to $\sigma_{ce} = 0.8$) and -1.5 (which corresponds to $\sigma_{ce} = 2.2$). Figure A.3 gives a graphical overview of the consumption nesting. Additionally, since the share of fossil fuels and share of electricity use are different between consumption and intermediate production, the prices of energies are differentiated based on their final use.

2.2.4 Data

The model builds on data from the Swiss energy input-output table (IOT) for the year 2005 (Nathani et al. 2011). In addition to the information on intermediate and factor inputs of more than 40 industries and service sectors, this table also includes detailed information on the production structure of various energy sources. This allows us to use this IOT to calibrate the cost functions of the different electricity technologies. It also holds detailed descriptions of household consumption of regular sector output and energy goods, and it includes data on physical and non-physical investments.

We have reduced the number of regular sectors to 10 to limit computational complexity. On the other hand, we have extended the table to include a larger variety of electricity sources using data from the Swiss Electricity Statistics. In total, the model differentiates between seven technologies for electricity generation (as indicated in Equation 2.7) and three fossil fuel categories. Table 2.3 provides an overview of all sectors and technologies.

Table 2.3: Overview of the sectors and technologies used in the model

Sector/Technology	Abbreviation
Agriculture	agr
Chemical Industry	chm
Machinery and Equipment	mch
Construction	con
Transport	trn
Banking and Financial Services	bnk
Insurances	ins
Health	hea
Other Services	ose
Other Industries	oin
Delivered Electricity	ele
Hydro Energy	hyd
Nuclear Energy	nuc
Electricity from Waste	wel
Conventional Thermal Plants	ctp
Solar Energy	sun
Wind	win
Biomass	bio
Refined Oil Products	oil
Gas	gas
District Heat	dhe

Parameter values are mostly identical to the original model version, they are presented in Table 2.4. We again assume relatively low elasticities in most cases to prevent overly optimistic model results due to unrealistic substitution potentials. Whenever possible and available, the values are taken from existing studies.[15] Together with the share parameters α which can be calculated directly from the IOT, the elasticities of substitution are the

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[15]See van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process, Hasanov (2007) for estimations of the intertemporal elasticity of substitution in consumption, and Donnelly et al. (2004) for the Armington elasticities.

basis for the calibration of the model. As it is common in CGE modeling, the model is calibrated such that it reflects the base-year data given in the IOT. As in the original model, we use the capital share to calculate a reference growth rate that is equal for all sectors. This growth rate gives the benchmark path that can be used to evaluate the policy effects. Given the capital shares in the IOT, the optimum growth rate of the economy in the long-run without any policy is 1.33% per year. Further details on calibration are explained in Bretschger, Ramer and Schwark (2010, 2011).

2.3 Scenarios

The aim of this paper is to investigate the economic effects of a nuclear phase-out policy. The task runs parallel to another big challenge for energy policy, which is the drastic reduction of carbon emissions over the next decades. In Switzerland, a reduction of 20% (compared to 1990) until 2020 has already been decided upon and longer-term targets will follow in the context of an international framework. The analysis of a phase-out policy should take these targets into account, because they obviously affect the incentives and the possible reactions following a shut-down of nuclear energy.

We assume that the climate targets will have to be met in any case, i.e. irrespective of the plans concerning nuclear energy. We therefore construct a benchmark scenario (BAU) that includes a long-term emissions reduction target which is compatible with international climate targets, in particular the target of an average temperature increase of maximum 2° C. Calculating the world carbon budget that is compatible with this temperature increase and requiring Switzerland to converge to a world average per capita carbon emission by 2050, the country will have to reduce its emission from 40 MtCO2 in 2010 to 14 MtCO2 in 2050, which is a reduction of carbon emissions by 65%. Accordingly, this emission reduction target is part of our BAU. In the model, the target is achieved using a carbon tax that is levied on the use of fossil energy and whose revenues are redistributed to the representative household as a lump-sum transfer. The carbon taxes increase over time and are adjusted across scenarios in order to ensure the climate target is the same for all scenarios.[16] Considering the very small share of fossil fuels in electricity production in Switzerland, we assume that the carbon tax does not affect electricity generation. However, we include carbon emissions and carbon taxes where the electricity is distributed and transmitted to end use. Other than that, the benchmark scenario can be viewed as a business-as-usual scenario that does not include any other policy measures. In the energy sector, the carbon tax affects the use of fossil energies and hence the fossil energy production declines. Accordingly, the share of fossil energy in total energy aggregate decreases and more electricity is used as a substitute for fossils. In the absence of any additional incentives and policies in the BAU, the market shares of

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[16]With climate policies, the sectoral capital stocks exhibit a similar pattern like sectoral output, so that that capital is shifted to the non-energy intensive and capital-intensive sectors, see Bretschger, Ramer and Schwark (2011, p. 975/6).

Table 2.4: Parameter values for regular sectors and consumption

Parameter	Description	Value
σ_Y	Elasticity of substitution between Q and inputs from other sectors B	0.392 (agr) 0.848 (oil, chm gas, dhe) 0.518 (mch) 0.100 (ele) 1.264 (con) 0.352 (trn) 0.568 (oin) 0.492 (rest)
ε	Elasticity of substitution between the three inputs (Energy E, labor L and other inputs V)	0.7 (agr, oil, gas, dhe, ele) 0.52 (con) 0.55 (oin, chm, mch) 0.4 (rest)
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor R	0.3
σ_C	Elasticity of substitution between energy (C_y) and non-energy goods (C_e) in consumption	0.5
σ_{egy}	Elasticity of substitution between electricity and fossil fuels in intermediate production	1.5
σ_{ce}	Elasticity of substitution between electricity and fossil fuels in consumption	1.5
σ_{ele}	Elasticity of substitution between electricity electricity generation and distribution	0.5
σ_h	Elasticity of substitution between different generation technologies	10
θ	Inter-temporal elasticity of substitution in the welfare function	0.6
η	Trade ("Armington ") elasticities	3.2 (agr) 4.6 (mch) 3.8 (ele, oin) 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

the individual technologies in total electricity generation remain constant at their initial levels. This implies that nuclear energy contributes to electricity supply for the entire time horizon. The benchmark scenario is calibrated so that the economy grows at a constant annual rate of 1.28%, with a welfare loss of 1.2% compared to the economy under the optimum growth rate of 1.33% absent of any policy shocks. The time horizon for the simulation is 38 years (2012-2050), and the time step for the simulation is one

year.

Table 2.5: Summary of scenarios

Scenario	Climate Target	Nuclear Phase-Out	Capacity Constraints
BAU	yes (-65%)	no	no
$PO - FM$	yes (-65%)	yes	no
$PO - CC$	yes (-65%)	yes	yes

The phase-out plan is simulated in two policy scenarios. In both cases, we assume a smooth, gradual phase-out of nuclear energy until the year 2034, reflecting the currently envisaged operation time of 50 years for all existing nuclear power plants. The policy scenarios differ with respect to their treatment of future development of the non-nuclear electricity technologies and the assumptions on capacity limits. First, we simulate a scenario ($PO - FM$) where no quantitative constraints on the future electricity mix are made. The results of this scenario are derived under free market (FM) conditions where only demand and supply determine the outcome and no constraints on the use of any technology, except for nuclear, or of total electricity are imposed. An exception is hydropower: a recent report of the Federal Office of Energy (2012) shows that, even under idealized conditions, the expansion potential for hydro energy is relatively small in Switzerland. Hence, even under the assumption of a paradigm shift in energy policy towards an increasing political acceptance of the expansion of hydro energy and a corresponding change of the legal framework, the amount of additional capacities is strictly limited. Accordingly, we assume a maximal expansion of hydro energy of 10% relative to the base year level in all scenarios. Apart from this restriction, $PO - FM$ abstracts from any other limitations. Various technologies compete for marginal cost to gain market share. Technologies with lower cost are able to replace nuclear energy when it is phased out. New renewables (solar, wind, etc.) are expensive compared to other established technologies. $PO - FM$ thus shows a phase-out policy and the resulting electricity mix without assuming any political preferences or support for any specific combination of generation technologies.

Table 2.6: Market shares in scenario $PO - CC$ (Source: Prognos 2012, Table 4-9)

Year	hyd	nuc	ctp	wel	sun	win	bio
2010	0.57	0.39	0.03	0.01	0	0	0
2020	0.64	0.26	0.03	0.01	0.020	0.015	0.025
2035	0.69	0	0.10	0.03	0.095	0.035	0.060
2050	0.52	0	0.06	0.02	0.270	0.070	0.060

The second policy scenario ($PO - CC$) implements concrete projections for individual technologies, based on the Energy Strategy 2050 of the Swiss Government (see Prognos 2012), which serves as a policy guideline for a nuclear phase-out. Prognos (2012) provides detailed projections on the shares of new renewable technologies and on the future electricity mix following the governmental strategy, which reflects technical, environmental, and societal conditions for electricity generation. It also assumes a limited

potential for the expansion of hydro energy and imposes an upper limit for electricity from conventional thermal plants and from waste. The share of new renewable energy, most notably of solar energy, increases significantly. Given the low shares of new renewable energy of current electricity production and their relatively high marginal costs, it appears evident that these energy sources have to be supported by policy; only then the requested gains in market shares can be achieved. We therefore add a subsidy (which is technology- and time- specific) for renewable energy sources in this scenario. Table A.1 summarizes the policies and assumptions on technology development in the three scenarios. The exact target shares for individual technologies (following the "NEP" scenario, i.e. the New Energy Policy in Prognos 2012) are presented in Table 2.6. The resulting capacity rents are recycled in lump-sum fashion to the representative household.

2.4 Results

2.4.1 Aggregate consumption and welfare

In the BAU scenario, aggregate consumption grows at an annual rate of approximately 1.28% on average during the simulation time horizon. Given the drastic changes evoked by the nuclear phase-out one might expect significant changes for future development. On the other hand, the counteracting forces of rising renewable energies and induced innovations and capital investment might mitigate the original effects. Indeed, this is what the results of our model suggest. As can be seen from Table 2.7, the consumption growth rates in the two phase-out scenarios are only marginally lower than in the BAU. In the $PO-FM$ scenario, the annual growth rate is 1.27%, and in the $PO-CC$ scenario, the rate is 1.26%. The associated welfare losses (measured by the decrease in total aggregated discounted consumption) are 0.10% for $PO-FM$ and 0.40% for $PO-CC$, respectively. The discounted accumulative GDP losses are 0.12% for $PO-FM$ and 0.53% for $PO-CC$.

Table 2.7: Average annual consumption growth rates, welfare and GDP losses

Scenario	Consumption growth rate	Welfare loss	GDP loss
PO-FM	1.27%	0.10%	0.12%
PO-CC	1.26%	0.40%	0.53%

Note: Welfare loss and GDP loss is calculated in % change versus BAU.

These results show that the aggregate effects of a nuclear phase-out policy are not negligible, but not as large as shown in other studies (see e.g. Marcucci and Turton 2012). There are multiple explanations for this result. First of all, the stringent climate target (65% of emission reduction) has already imposed strong impacts on the economy. Carbon taxes increase the production cost for firms of all sectors (where energy aggregate is one of the essential inputs) and thus reduce the demand of fossil energies. This gives incentive for firms to seek ways to improve their technology efficiency on one hand, and

enforce the substitution between energy and other factor inputs on the other hand. This type of substitution has indeed reduced the demand for electricity as well because firms use energy aggregate as a whole to produce intermediate goods. Nuclear phase-out works as a complementing policy for emission mitigation, which makes it much easier to reach both climate and nuclear target in the same time. Another important factor is planning reliability for investors. The phase-out increases the incentives to invest in alternative electricity technologies, which leads to a reduction in the cost of these technologies and a smoother and less costly adoption of the economy. In a setting where innovation and growth are directly interrelated, these additional investment incentives contribute significantly to lowering the cost of the phase-out. Third and related to that, investments in all parts of the economy are fostered, because capital becomes cheaper relative to energy. Note, however, that we assume that the phase-out policy (like the carbon policy) is announced at the beginning and the phase-out pattern is known to all actors in the economy.

The differences between the two policy scenarios can be explained by the assumptions on technology restrictions. In $PO - FM$, aggregated costs are lower because no subsidies have to be paid for less competitive technologies, which means that lower cost technologies gain larger market shares and new renewables continue to contribute relatively little to electricity generation (see below). Fading input of fossil fuels is to a large part compensated by increasing capital and its productivity. On the other hand, $PO - CC$ shows that the promotion of new renewables does not impose a significant drag on the growth rate of the economy. On the contrary, it highlights that a substantial increase of renewable electricity generation is possible at relatively low cost. Compared to $PO - FM$, there is more substitution of decreasing fossil fuels within the energy sector in the case of $PO - CC$.

To meet the requirements of climate policy we posit a continuously rising carbon tax over time. In 2050, the carbon tax in $PO - CC$ is 7.1% higher compared to the tax in $PO - FM$, while the carbon tax in $PO - FM$ is about 3.7% higher compared to the tax in BAU. Due to the low initial market share of solar, a huge expansion of capacity is needed in order for solar energy to take up more than 20% of the electricity market in $PO - CC$ from current share of less than 1%. To achieve the market share target, the capacity expansion in generation and back-up has to be partly financed by subsidies. This cost is the sunk cost incurred before producing electricity. Subsidies are endogenously determined by the model in order to achieve the market share target. From our simulation results, the cost for 1KWh electricity produced from solar is about 0.10 Swiss Francs with the subsidy of 0.04 Swiss Francs in 2035, the year after the nuclear plants are completely shut down; In 2050, the costs decrease to 0.06 Swiss Franc per KWh. However, new capacities' increase in the last 15 years of the simulation are twice the size of the increase between 2012 and 2034; hence, consumers still have to pay 0.03 Swiss Francs as a subsidy to compensate for new capacities in 2050.

To test the robustness of our findings we perform a sensitivity analysis and vary important model parameters. Given the research question of this paper, the elasticity of substitution between electricity and fossil energy (both in production and in consumption) plays a crucial role. We had set these elasticities (σ_{egy} and σ_{ce}) to 1.5. We consider two alternative assumptions. First, we reduce the values to 0.8 (Sue Wing *et al.* 2011) and thus (pessimistically) assume poor substitution between the two energy sources. This restriction limits the possibilities for further reduction of carbon emissions and a quicker development of new renewables. As a second variation, we increase the values of the elasticities to 2.2, which implies a higher substitution potential.

The resulting effects on welfare are shown in columns 1 and 3 of Table 2.8. As can be seen from Table 2.8, the assumption of poor substitutability has quite a strong impact on consumption growth and welfare, especially in scenario $PO-CC$. In this case, substitution within the energy sector is aggravated, and impacts on the rest of the economy are stronger. Additionally, higher carbon taxes are necessary to reach the climate target, and new renewables have to be subsidized at a higher rate. This decreases real income of households and leads to a significant drop in consumption growth. On the other hand, under ideal conditions (i.e. a minimal degree of restrictions in technology expansion and a high degree of substitutability between the two energy sources), even a welfare gain compared to BAU is possible. Generally, better substitutability lowers the cost in welfare terms of the phase-out policy and leads to higher growth rates for consumption.

Table 2.8: Annual consumption growth rates and welfare losses under different assumptions for σ_{egy} and σ_{ce}

	0.8	1.5	2.2
PO-FM			
Growth rate of consumption	1.22%	1.27%	1.29%
Welfare loss	0.6%	0.1%	-0.2%
PO-CC			
Growth rate of consumption	1.16%	1.26%	1.28%
Welfare loss	2.5%	0.4%	0.2%

Figure 2.1 shows the range of consumption growth rates under different values for σ_{egy} and σ_{ce} in the *PO-CC* scenario. The core range (grey area in Figure 2.1) goes from a rate of 1.16% for $\sigma_{egy} = \sigma_{ce} = 0.8$ to a rate of 1.28% for $\sigma_{egy} = \sigma_{ce} = 2.2$. The dashed line shows the *BAU* case (with $\sigma_{egy} = \sigma_{ce} = 1.5$). The variations in consumption growth can be further affected by the elasticity values. Lower elasticities depress the aggregate consumption growth, while higher elasticity values give more room for substitution between energy sources and thus increase consumption.

We also check other elasticities of substitution which may have impacts on aggregate consumption. Trade elasticities (η) affect the aggregate consumption, however, the effects are relatively insignificant. Lower trade elasticities encourage domestic production and

Figure 2.1: Projected aggregate consumption growth path in *PO-CC*

increase consumption while higher values decrease consumption. Technology substitution elasticity (σ_h) has relatively large impacts on consumption compared to the trade elasticities. A lower elasticity of substitution between technologies means that it is much difficult to replace one technology with the other. Because there is no cost incurred in the model when replacing nuclear with other technologies, we use a lower value to implicitly capture the sunk cost that invested in different technologies in order to expand capacity or to build storage facilities. Holding other parameters the same as in PO-CC, we find that the growth rate of consumption decreases to 1.25% in the case $\sigma_h = 5$, with a welfare loss of 0.51%. On the other hand, a higher value for the elasticity of substitution ($\sigma_h = 20$) reduces the barriers for substitution between technologies. Doubling the value of σ_h to 20 will increase the growth rate of consumption to 1.264% with a welfare loss of 0.3%. The growth rate can reach up to 1.31% in the most favorable case[17]. Moreover, better substitution between generation technologies lead to lower subsidies to expand renewable energies. Consumption rates outside of the core range are derived under extreme assumptions. if we restrict our attention to more realistic cases (most notably values above unity for the two elasticities), aggregate effects on consumption and welfare is robust, and the uncertainty on the magnitude of the aggregated effects can be reduced significantly.

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[17]This is the PO-CC scenario with higher values elasticity of substitution where $\sigma_{egy} = \sigma_{ce} = 3$ and $\sigma_h = 20$.

2.4.2 Energy use and electricity generation

Both fossil fuels and electricity are used in the production of intermediate goods and for consumption. Let *egyi* and *egyc* denote aggregate energy use (i.e. the use of electricity and fossil fuels) in intermediates production and consumption respectively. Table 2.9 shows that the nuclear phase-out leads to a significant decrease in energy use, most notably in intermediate goods production. Producers substitute away from energy as an input, and the energy efficiency of the economy as a whole increases. We can also observe that the nuclear phase-out leads to an additional reduction in fossil energy use, both in intermediate goods production (*fosi*) and in consumption (*fosc*). This confirms the intuition that a combination of a climate target and a reform of the electricity sector facilitates the reduction of emissions, because it induces both producers and consumers to lower their demand for energy goods. Finally, the last two rows of Table 2.9 indicate that electricity use is also reduced significantly. This can be explained by the fact that the BAU scenario assumes only a climate target, which leads to an increased electrification of the economy. This trend is reversed to some extent in the two phase-out scenarios.

The effects are stronger in $PO - CC$ for all of the variables in Table 2.9. The free choice of the electricity mix and the absence of any political or technological constraints (with the exception of hydro energy) in $PO - FM$ allow for a less costly transition to a nuclear-free electricity sector. This leads to a less significant reduction of energy use, to less substitution for other inputs and consequently to a less pronounced shift to a less energy dependent economy. The results for scenario $PO - CC$ show that combining the phase-out plan with supportive measures for new renewable energy sources also leads to a faster reduction of emissions and to more energy efficient production in general.

Table 2.9: Use of aggregated energy, fossil energy and electricity (% change vs. BAU)

Variable	Scenario	2020	2035	2050
egyi	*PO-FM*	-2.50%	-8.34%	-7.04%
	PO-CC	-6.52%	-20.2%	-21.1%
egyc	*PO-FM*	-0.28%	-0.81%	-0.94%
	PO-CC	-1.49%	-6.59%	-8.27%
fosi	*PO-FM*	-0.40%	-1.86%	-1.87%
	PO-CC	-1.12%	-4.91%	-5.73%
fosc	*PO-FM*	0.69%	1.03%	-0.16%
	PO-CC	1.76%	1.86%	-0.20%
ele	*PO-FM*	-3.63%	-10.5%	-8.07%
	PO-CC	-9.40%	-24.9%	-24.1%
Y_{ele}	*PO-FM*	-5.44%	-17.3%	-14.3%
	PO-CC	-14.1%	-41.1%	-42.4%

Figures 2.2 and 2.3 show the shares of different electricity generation technologies on total electricity generation in the scenarios $PO - FM$ and $PO - CC$. Figure 2.3 replicates the target shares from Table 2.6, while Figures 2.2 and shows the shares derived under free market conditions in scenario $PO - FM$. The Figures show that in the absence

of significant constraints and support for new renewables, it is mostly the established technologies that replace nuclear energy. The new renewables on the other hand do not gain sufficiently high market shares and remain almost insignificant. Since there are no constraints for technologies expect for hydro, technologies with lower marginal cost are able to gain market share, replacing the nuclear energy. New renewables (solar, wind, etc.) are expensive compared to other established technologies. Moreover, current capacities of new renewables are very small. It requires heavy investment to increase their capacities. We do not distinguish fixed cost and marginal cost in the model, so that the cost of producing one more unit of electricity out of the capacity is larger for new renewables. In $PO-CC$, the assumed physical limitations for *hyd*, *ctp* and *wel* lead to an increase in the cost of these established technologies. This is an additional explanation for the low additional cost in welfare terms discussed above. The reduced attractiveness of the established technologies facilitates the transition to an electricity sector that is increasingly dominated by new renewable technologies.

Moreover, the market share of new renewables in the electricity market needs to be significantly increased in $PO-CC$. This is hardly possible without government subsidy on new renewable technologies such as solar, wind. The government subsidy drives down the cost of producing electricity using such technologies, making them competitive compared to the established technologies. It also helps to attract new investments, and hence capital stock increases and helps renewable technologies to build up their capacities for large scale production in order to meet the policy target. These reasons explain why solar faces a drastic increase in the $PO-CC$ scenario. Without any support for new renewables, they will not be able to gain a significant market share, because the market mechanism will choose to produce electricity from technologies with large market shares in the benchmark because large market share in the benchmark means that technology is more profitable to produce than others. So under the free market scenario ($PO-FM$), when nuclear phases out, electricity generation from hydro will increase first rather than other technologies. The renewables increase with a small value since they are less than 1% in the beginning.

Figure 2.4 illustrates the total electricity generation in different scenarios. The average annual growth rate of electricity generation in BAU is calibrated to be 1.28%, which means the total electricity generation in 2050 is about 1.6 times the level in 2012. In *PO-FM*, the total electricity generation declines by 14.3% in 2050 compared to BAU, which is about 1.4 times the level in 2012. The output from electricity sector in 2050 further decreases to approximately the level of today in *PO-CC*.

Finally, even though the CITE model is a one-country model, we can also draw some conclusions on the impacts on electricity imports and hence on foreign dependency. y_{ele} in Table 2.9 indicates domestic production of electricity (or the total output of the electricity sector as described by Equation 2.6). Compared to *ele* (which in fact describes the change in the use of the corresponding Armington good), Y_{ele} decreases more, which

Figure 2.2: Share of generation technologies in *PO-FM*

indicates an increasing difference in domestic electricity use and domestic electricity production and hence an increase in imports. In scenario $PO - CC$, the decrease in Y_{ele} relative to BAU is about 40%. In absolute terms, this means that domestic electricity generation remains more or less at the level of today. However, electricity use decreases only by about 24%. Again measured in absolute terms, this figure implies an increase relative to the initial level and hence an increasing need for imports. The differences between the two scenarios can again be explained by the more restrictive assumptions on technology expansion in scenario $PO - CC$. These results are in line with Marcucci and Turton (2012) who abstract from endogenous capital formation and therefore obtain losses which are higher than those of our calculations.

2.4.3 Sectoral output

Using a less complex version of the CITE model, Bretschger, Ramer and Schwark (2011) show that climate policy will induce a certain structural change of the economy. These findings are strengthened by the results derived from the policies simulated in the present paper. Highly innovative sectors and/or sectors with a relatively low dependency on electricity (*chm*, *mch* and most of the service sectors) become relatively more important and gain higher market shares. On the other hand, energy-intensive sectors such as *trn* or *oin* (which includes all the heavy industries) grow at lower rates compared to the *BAU* scenario and therefore contribute less to total output of the economy. Fossil energy production sectors exhibit negative growth rates, indicating an increased shift away from fossil energy use in the two phase-out scenarios. The results derived here are similar in direction compared to Bretschger, Ramer and Schwark (2011), but slightly larger in

Figure 2.3: Share of generation technologies in *PO-CC*

magnitude due to the extension of political intervention to the electricity sector.

Table 2.10: Annual growth rates of regular sectors and fossil energy sectors in the phase-out scenarios

Sector	*PO-FM*	*PO-CC*
agr	1.02%	0.95%
chm	1.53%	1.61%
mch	1.52%	1.67%
oin	0.94%	0.87%
con	1.32%	1.31%
trn	1.11%	1.07%
bnk	1.34%	1.33%
ins	1.45%	1.43%
hea	1.33%	1.33%
ose	1.32%	1.32%
oil	-1.93%	-1.95%
gas	-1.45%	-1.45%
het	-1.72%	-1.69%

Table 2.10 summarizes the sectoral growth rates. As already indicated above, structural change is clearly directed towards innovative sectors (*mch* and *chm*) and sectors with low energy intensities (*ins*, *bnk*, *hea*, *ose*). Structural change is amplified in scenario *PO − CC*. Under more restrictive conditions and the resulting higher costs of the phase-out, resources are increasingly reallocated to innovative and less energy-dependent sectors. This leads to a higher divergence of sectoral growth rates and a larger degree of structural change.

Figure 3.5 illustrates the differences in the two scenarios and the impacts on the degree

Figure 2.4: Total electricity generation across scenarios

of structural change. Figure 3.5 shows the growth paths of two selected sectors in the two phase-out scenarios. *mch*, a particularly innovative sector, benefits the most in both scenarios. *oin* (e.g. cement, pulp and paper) on the other hand experiences the highest drop compared to BAU both in scenario $PO - FM$ and $PO - CC$. As can be seen, the difference in output in 2050 is substantially larger in scenario $PO - CC$. The (politically desired) shift to an electricity sector dominated by new renewable generation technologies is thus accompanied by a "greening" process in the economy where energy intensive sectors become less important. The shaded areas illustrate that the assumptions on technology expansion have a pronounced impact on individual growth rates. Given that more restrictions tend to lead to a higher divergence of sectoral growth rates, scenario $PO - FM$ indicates the minimum (or the bottom limit) of structural change that can be expected to result from a phase-out policy under the given conditions.

Again, we want to test the reliability of the results in terms of a sensitivity analysis. On the sectoral level, poor substitutability between the two energy sources amplifies the structural change. Figures 2.6 and 2.7 illustrate the intensified structural change in both scenarios when reducing the elasticities to $\sigma_{egy} = \sigma_{ce} = 0.8$. As indicated above, poor substitutability in the energy sector leads to larger impacts on the rest of the economy, to a more pronounced reallocation of resources and investments to innovative and less energy dependent sectors and thus to larger structural adjustments. These effects are significantly stronger in scenario $PO - CC$. In this scenario, the costs of the phase-out are higher in any case, and the assumption of poor substitutability leads to an even more pronounced change of the structure of the economy. The opposite holds under better substitutability. However, the effects of these adjustments are much weaker in this case.

Figure 2.5: Range of growth rates for selected sectors across scenarios

Nonetheless, Figures 2.6 and 2.7 indicate that higher values for σ_{egy} and σ_{ce} mitigate the structural changes and lead to a lower difference in sectoral growth rates.

Figure 2.6: Average sectoral growth rate in *PO-FM*

These sensitivity checks show that the main results of our study continue to hold under varying model assumptions. But the costs of the phase-out depend crucially on whether we presume relative complementarity (i.e. values below unity) or good substitutability between energy sources. However, if we focus only on cases where both σ_{egy} and σ_{ce} are set above unity, the variation in the magnitude of the observed effects is reduced considerably. We consider this to be the relevant case, and therefore conclude that our results are robust under realistic assumptions, both in direction and magnitude.

Figure 2.7: Average sectoral growth rate in *PO-CC*

2.5   Conclusions

In this paper, we analyze the economic effects of a gradual nuclear phase-out policy in Switzerland. Due to its relatively high current share of nuclear energy of total electricity generation, its high investment rates and its significant research activity, Switzerland is a good case to study the implications of such a policy in an innovative, developed economy. The analysis is conducted using a CGE model with endogenous growth and a detailed representation of the Swiss electricity sector. We find that a gradual phase-out of nuclear energy until the year 2035 combined with a longer-term emissions reduction target results in up to 0.4% of welfare loss. It also leads to structural adjustments in the economy. The magnitude of these impacts depends on the assumptions and the restrictions on the expansion and the capacities of replacement technologies. In the free market scenario $PO - FM$, the phase-out can be achieved at the cost of 0.1% welfare loss and with only moderate adjustments in the structural composition of the economy. Imposing capacity limits for established technologies and target shares for new renewable electricity sources (as in scenario $PO - CC$) increases the welfare loss from 0.1% to 0.4%. Evidently, the planned reorganization of energy supply aims at substantially decreasing external costs of energy use, which raises welfare of the consumers. The studied policies also accelerate the greening process of the economy by redirecting more resources and investments towards innovative industries, energy-extensive sectors and new renewable technologies.

The results highlight that innovative economies have the potential and the capacities to achieve ambitious targets in the electricity sector, and that a reform towards an electricity generation sector dominated by new renewables is economically feasible. An important model assumption concerns the perfect information of investors on current and future

policies. Given the long horizon of energy policy, the results highlight that the innovative potential of the economy can only be fully exploited if the regulatory frameworks are announced at an early stage and the corresponding targets receive political support over a sufficiently long time period.

The analysis could be extended in various respects. An important aspect excluded in this paper are the external costs of nuclear energy. These costs are, however, hard to quantify, and the existing estimates vary significantly. Additionally, secondary benefits of reduced emissions (in the form of a positive impact on productivity and/or welfare) could also be included. Both of these extensions would most probably contribute to a further reduction of the policy costs derived in this paper. However, there are other factors may lead to underestimate the welfare loss. Capital invested in electricity sectors is technology specific. It exhibits a slow rate of turnover and a high degree of sunkness. This will lead to additional cost to retrofit or scarp plants. Furthermore, new renewable energy requires back-up capacity to secure the stable power supply. The higher the penetration of renewables in the system, the more back-up capacity is needed. This is not considered in this paper. All these aspects are left for future research.

3 Evaluating social cost of energy transition within the endogenous growth framework

3.1 Introduction

Energy transition can be seen as a process of technical innovation and resource substitution into a stage of sustainable energy use. It usually takes time to accomplish, and the greater the degree of reliance on a particular energy source, the more widespread the prevailing uses and conversions, the longer their substitutions will take (Smil 2010). However, this is also one of the most pressing challenges for the whole world in order to achieve the internationally agreed on two-degree climate target. Many countries have initiated their own energy transition profiles in the long run. Germany published a policy document outlining the energy transition it will face until 2050, including aspects such as greenhouse gas reduction of 80%-95% by 2050 and renewable energy taking up to 60% share by 2050. Its final goal is the phase-out of coal and other non-renewable energy sources (FME 2012). France, which is heavily dependent on nuclear power, has launched a national debate on the government's proposals for an energy transition involving reduction of nuclear power and the development of more renewable dependent system. Switzerland has the so-called "Energy Strategy 2050" regarding energy transition to offer an economically and environmentally sustainable energy supply for the country's needs. This strategy focuses on three priorities: boosting energy efficiency, increasing the share of renewable energy, and meeting any remaining requirements through imports or electricity production from gas.

The transition toward a low-carbon economy is not free. It is for sure that Switzerland will face many challenges to cut CO_2 emissions while also phasing out its use of nuclear power. Possible consequences include rising energy prices, switching to more expensive energy sources, or a higher dependence on foreign supply. However, if the government is in favor of the development of renewable resources, providing both fiscal and political support, some of the challenges can be tackled without incurring additional cost. Countries like Switzerland, having few or no indigenous fossil fuel resources are unsurprisingly at the

forefront of the solar revolution. Moreover, the Swiss Energy Foundation (SES) has shown in a study that the energy transition in Switzerland may create 85,000 new jobs by 2035, if the country taps the potential for increasing energy efficiency and expanding renewable energy.[1]

To develop a deeper understanding of the social cost of energy transition an economy will face in the future, I use the Swiss economy as a case study, together with an endogenous growth model to investigate three critical assumptions which can affect the potential social cost of energy transition. Combining the Swiss government strategy and the latest studies of Prognos (2012), an energy package is designed to illustrate the energy transition strategy of Switzerland, which includes 65% of greenhouse gas emission reduction by 2050, complete nuclear phase-out until 2034, and a quick expansion in renewable resources, particularly for solar energy. Given this energy policy, I follow a stepwise strategy to answer three research questions in order to give a complete answer on the estimation of energy transition cost for an economy.

My first question is how the economy reacts when the macroeconomic environment for investment changes. This question is due to the concerns about uncertain future development. Switzerland has experienced a steady growth of capital in the past decades. Due to the global economic crisis, Switzerland is booming due to the "safe haven" perception and vast inflows of foreign capital. This can change the investors' investment strategy and thus the growth potential of sectors in the economy.

As a long-term process, energy transition can affect the future generations as well. Hence, the second question appears is how to value future generations? This is one of the environmental economists' major concerns for life-cycle analysis. It is common to assume a social discount rate to estimate the present value of future periods. What is an appropriate value for this discount rate? If it retards the investment and private entrepreneurship needed to innovate, certain generations may be impoverished, leading to a distortion in social welfare.

The third issue to be investigated is: can the society provide sustainable innovation for the growth in the long run? Innovation triggers further growth. The degree of innovativeness of the economy is decided by the capital share in production. Since new knowledge is the results of capital investment, failure to support innovation may cause serious consequences for the growth of knowledge intensive sectors, which can be passed on to other sectors through the inter-linkage between sectors.

Several papers have studied parts of the three questions raised above. Nordhaus (1992) finds the net economic costs can be modest if the transition follows the optimal path. Kemp et al. (2007) describe the Dutch energy transition model and highlight the success of reflexive governance on achieving sustainability goals. Stern (2007) points out that

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[1] http://www.energiestiftung.ch/energiethemen/energiepolitik/energiewende/85000-jobs/

low discount rate may augment the cost of climate change to a loss of GDP per capita up to 35% in 2200 if no political actions take place. Stephan and Mueller-Fuerstenberger (1998) find that higher discount rate leads to significantly lower emission reductions. Recent research by Bretschger et al. (2012) indicate the complete nuclear phase-out can be achieved with relatively low costs if renewable technologies are used as a substitute. This is in line with the results of Welsch (1998), and Boehringer, Wickart and Mueller (2001).

This paper contributes to the literature for providing a better understanding the factors that impact the long-term estimation of energy policy cost. First, I investigate the impacts of the energy transition under different macroeconomic environments which largely determines the potential growth of an economy. Second, I corroborate my analysis by investigating the impact of innovativeness, to exploit how the sectoral growth is dependent on innovation and capital investment in production. Finally, I show how the sectoral growth and social welfare are affected by the intertemporal discount rate in a dynamic setting.

I find that energy transition can be achieved at moderate cost in general. Higher capital growth will push the economic structure toward diversification instead of specialization. The effects of innovativeness on sectoral growth are determined by several forces. Knowledge dependent sectors grow at a lower rate compared to labor intensive sectors. Less productive use of capital for innovation can also produce negative effects on substituting fossil energies. Discounting of future generations has only mild effects on sectoral growth in a dynamic world. However, people have to pay more when lowering the discount rate.

The remainder of the paper is organized as follows. Section 2 gives a brief introduction of the general equilibrium model with endogenous growth. Section 3 describes the data and scenarios used for computational analysis. Section 4 presents the results and discusses the findings. Section 5 includes sensitivity analysis on different energy transition paths. Finally, section 6 concludes.

3.2 The methodology of CITE model

The CITE model is a multi-sectoral CGE model with fully endogenous growth mechanism. The growth is described in an expansion-in-varieties fashion based on Romer (1990). I use the latest version of the CITE model to analyze how the Swiss economy accommodates with energy transition policies. In particular, I investigate circumstances where the renewable energies are supported by the government to replace fossils and nuclear, under different growth trajectories.

The macroeconomic structure is described in Bretschger et al. (2011). The bottom-up representation of the energy sector is presented in Bretschger et al. (2012). I include

a brief description of the model settings here and highlight several crucial components only. A graphical representation of the model nesting in production and consumption is given in the Appendix.

Production in each non-energy sector, which we call "regular" sector, is represented by a three-stage nested CES function, see Figure A.1 in the Appendix. In the first nesting, both intermediate composite (Q) and regular output composite (B) are used for the production of final goods (Y). In the second stage, the intermediate composite goods (Q) are produced by combining the accumulable capital (J) with other inputs (X_j). Investment is distinguished into physical investment and non-physical investment. Outputs from regular sectors (NE) are used for physical investment. Non-physical investment requires research labor together with research in R&D as inputs. The capital accumulation and investment decision process are formulated in an usual way. In the bottom nesting, factor inputs and energy are used as essential inputs to produce intermediate goods (X_j). The final goods (Y) producer's problem and the intermediate composite producer's problem in each sector can be formulated as:

Final goods producer:

$$\max_{Q,B} p_Y Y - p_Q Q - p_B B \tag{3.1a}$$

Intermediate composite producer:

$$\max_{X_j} p_Q Q - \int_{j=0}^{J} p_X X_j dj \tag{3.1b}$$

$$\max_{NE} p_B B - \sum_{ne} p_{ne} NE \tag{3.1c}$$

where p_Y, p_Q, p_B, p_X, p_{ne} are the price of final good Y, price of intermediate composite Q, price of output composite B, price of intermediate good X, and price of regular goods ne. And the production of intermediate goods X_j can be written as:

$$X_j = J[\phi L_j^{\frac{\epsilon-1}{\epsilon}} + \eta E_j^{\frac{\epsilon-1}{\epsilon}} + (1-\phi-\eta)V_j^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}}, \tag{3.2}$$

where L is labor, E is energy, and V is public capital; ϵ is the elasticity of substitution between three inputs; phi, η, and $1-\phi-\eta$ are the share parameters.

The energy sector is constructed in a similar way (see Figure A.2). It comprises two energy sources: fossil fuels and electricity, which is the top nesting of the energy production (See 3.3a). Three technologies are considered in the production of fossil fuels: oil(oil), gas(gas), and district heat(dhe). They are assembled by the Cobb-Douglas approach on the second stage. While electricity services are provided to end use by combining the pure electricity generation and electricity supply (transmission and distribution). In the lowest nesting, the electricity is generated in a bottom-up fashion. Utility companies

choose the cheapest technologies according to the cost function to produce electricity. In the model, seven technologies can be used for electricity generation: hydro(hyd), nuclear(nuc), waste(wel), conventional thermal plants(ctp), solar(sun), wind(win), and biomass(bio).

$$E_j = [\alpha_{ele,j} ELE_j^{\frac{\sigma_{egy}-1}{\sigma_{egy}}} + (1-\alpha_{ele,j})FOS^{\frac{\sigma_{egy}-1}{\sigma_{egy}}}]^{\frac{\sigma_{egy}}{\sigma_{egy}-1}} \tag{3.3a}$$

$$ELE_j = [\alpha_{gen,j} GEN^{\frac{\sigma_{ele}-1}{\sigma_{ele}}} + (1-\alpha_{gen,j})DIS^{\frac{\sigma_{ele}-1}{\sigma_{ele}}}]^{\frac{\sigma_{ele}-1}{\sigma_{ele}}}, \tag{3.3b}$$

where ELE is electricity aggregate, FOS is fossil energy aggregate, GEN is the electricity generation, DIS is the electricity distribution and transmission. $\alpha_{ele,j}$ and $\alpha_{gen,j}$ are the share parameters and σ_{egy} and σ_{ele} the substitution elasticities.

For consumers, a representative, infinitely lived household allocates her factor income between consumption and investments under perfect foresight and in accordance with intertemporal utility maximization. The agent consumes both regular goods and energy goods. In the lowest nesting, various regular goods are substitutable, fossil fuels and electricity also substitute with each other to a certain extent (See Figure A.3). The household problem can be written as:

$$\max_{C_t}[\sum_{t=0}^{\infty}(\frac{1}{1+\rho})^t C_t^{1-\theta}]^{1/(1-\theta)} \tag{3.4a}$$

s.t.

$$p_{W,t+1}W_{t+1} = (1+r_{t+1})p_{W,t}W_t + \sum_f w_{f,t}F_t - p_{C,t}C_t \tag{3.4b}$$

where ρ is the intertemporal discount rate, θ represents intertemporal substitution, C_t is the consumption at time t, W_t is the assets of the household at time t, r is the interest rate, f denotes the factor inputs including worker labor, research labor, public capital, and $w_{f,t}$ is the respective prices, $p_{C,t}$ is the consumer price index. Hence equation 3.4b describes the budget constraint in each time period.

3.3 Data and scenarios

This study uses the same data set as described in Chapter 2. To calibrate the numerical model, sectors in the Swiss energy input-output table are aggregated into 7 sectors for electricity generation, one sector for electricity distribution and supply service, and 3 sectors for non-electricity energies (See Table 2.3 for details). Table 2.4 presents the parameter values and elasticities.

Different from Chapter 2, the benchmark scenario is a business-as-usual scenario that does not include any other policy measures. The change in welfare level in other scenarios

is hence compared with the benchmark value. In order to reflect the energy transition during the simulation period, energy policies have to be added into the model. An energy policy package is considered to be binding, no matter how the economic situation is. This package includes three aspects: first, reducing carbon emissions by 65% relative to the intial period until 2050; second, the nuclear power plants have to be shut down completely until 2034 (reflecting 50 years of operation time for all existing nuclear power plants); third, the government supports the development of renewable energies in electricity generation industries. The expansion of different generating technologies follows the estimation of Prognos (2011) (See Figure 3.1).

Figure 3.1: Pre-designed energy transition 2012-2050

3.4 Simulation results and analysis

3.4.1 Uncertain future reflected by capital growth

One challenging issue for economic analysis is the uncertainty of future development for an economy. Many factors such as domestic deficit, global crisis can affect the macroeconomic environment for investment and consumption decisions, and hence the overall growth of an economy. Various growth trajectories and outliers are necessary to be taken into consideration for a complete analysis.

In the original model of Bretschger et al. (2011), the capital growth is assumed to be 1 %, which corresponds to the growth of the economy at the rate of 1.33%. This is consistent with a simple average of historical growth rates. To be more precise, I use the

so-called Markov Chain analysis to estimate the possibilities of future growth convergence in the long run (Details in Appendix). The results show that we can expect the Swiss economy to experience a favorable growth between 0 and 1.5% with the probability of 33%, between 1.50% and 3.0% with the probability of 35%. This result is in agreement with that of OECD (2012) estimates which reports that the average growth rate in GDP for Switzerland between 2011-2060 will be 2.1%. Even in per capita level, the growth rate is 1.7%, falling into the steady growth group (growth rate between 1.5 and 3%) in my analysis.

Rudolf and Zurlinden (2009) estimate the growth rate of capital to be between 1.90% and 2.38% in the period 1990-2005 based on different definitions. Data from Swiss Federal Statistical Office also shows that the average growth rate of capital between 1990 and 2005 is about 2.5%.[2] These estimations are all far above the value used in the previous analysis (which is 1%). Hence, I define various growth rates (1.5%, 2% and 2.5%) for capital to further the CGE analysis so as to incorporate information on the new estimates.

When setting the capital growth rate to be 1%, the growth of consumption in the energy package scenario is approximately 1.259%, which is lower than the growth rate of GDP when no energy policies are implemented (which is 1.34%). The 0.07 percentage point loss follows from the energy policy shocks, resulting in 1.7% welfare loss compared to the baseline without energy policies.

As recent studies show (Rudolf and Zurlinden, 2009), the growth rate of capital used in the model is underestimated. We elaborate our analysis by incorporating these new results in order to reflect the true effects on the economy. Intuitively, raising the capital growth rate will contribute to higher growth of sectoral outputs and hence of the whole economy. As we can see from Figure 2, the dashed lines indicate the baseline scenarios where the energy policies are absent, while the colored lines show the scenarios when energy policies are taking place. All colored lines are underneath the dashed lines, showing that energy policies indeed negatively impact the economy.

Follow the BGP described by growth theory, each additional percentage point of growth in capital produces 1.34 additional percentage points of output growth, as well as aggregate consumption. The growth rates of aggregate consumption in higher capital growth scenarios are 1.93% for capital growth rate of 1.5%, 2.60% for 2.0%, 3.27% for 2.5%, respectively, confirming our intuition from theory. The welfare loss compared to their respective baseline scenarios are the same, which is approximately a decline of 1.7%.[3] However, higher capital growth leads to higher output growth. That means, with the same share of welfare loss, the economy in absolute terms suffers more severely in high capital growth case that that of low capital growth case. The increasing gap in Figure 2

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[2]The growth rate of capital between 1990-2010 is about 1.98% (nominal) and 1.58% (real), calculated based on data from Swiss Federal Statistical Office.

[3]As indicated in Figure 3.2, the 1.7% welfare loss is due to the lower value of the colored lines compared to the respective dashed lines lying just above it.

Figure 3.2: Growth of consumption with different capital growth

between baseline growth path and respective growth path under policy illustrates this feature.

The sectoral effects under different capital growth rates are similar to the effect on aggregate consumption. The incremental for each of the sector's growth due to the rise of capital growth is 0.67% for additional 0.5% of capital growth. Put differently, the aggregate increase in capital stock is not proportionately distributed across sectors. For example, sector A in the beginning grows at the rate of 1%, 0.5% incremental of sectoral growth means it grows at the rate of 1.5% now, which is 50% increase; while if sector B grows at the rate of 2%, 0.5% incremental raises the growth rate to 2.5%, however the growth rate increases by 25% only. In the end, sectors with a lower growth rate can speed up with booming capital investment in the future, and reduce difference in sectoral output values. The change of sectoral share of GDP will finally adjust the structure of the economy towards an equal development. In contrary, low capital investment in the future can lead to specialization of the economy towards innovative and energy-extensive sectors where the return on capital is much higher.

The above analysis also suggests that securing the sustainable capital market can help an economy to develop an economic structure of "autarky" type instead of investing in some sectors which can produce high output while dragging other sectors into the mire. This is particularly important if the strategy of an economy is to be self-sufficient. In the context of global competition, foreign direct investment will play an important role as a major source of capital investment. This is one of the many reasons why emerging

economies put great efforts to attract outside money.

Figure 3.3: Sectoral growth rates with different capital growth

3.4.2 Uncertain innovativeness of an economy

The focal point of the endogenous growth model is that innovation contributes to additional output. Innovation, or say creation of new capital variety, comes from knowledge, particularly from new knowledge. However, it is not plausible to expect innovation contributes to economic growth at the same rate over time. Human-initiated innovation, like energy consumption and population growth, is a process that naturally saturates with rising global income levels and technological intelligence (Huebner 2005). The model assumes that the capital share in production is about 25%.[4]

As from theory it is the innovation that makes the whole economy grow at a higher rate than the growth rate of capital. The difference between the growth rate of capital and the growth rate of GDP implies the contribution of innovation on economic growth. As illustrated in Figure 3.4, the data for Switzerland demonstrate that innovation has been playing an important role since 1990s, though its effects on growth have been declining from mid-2000s onwards. The impact of innovation peaked around the year 2005, the global financial crisis since 2008 has shocked the economy and depressed its development even though it is doing better in mastering the current economic crisis than its recession-hit European peers. However, with the continuous low growth of world's

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[4]This is the value calibrated to replicate the average growth rate of capital and GDP in history. According to the aggregated Energy IOT, the lower bound for the share of capital in the energy and factor aggregation is about 26% (in sector *con* and *hea*), the accumulative capital used to cover innovation cost in intermediate production can not be larger than 26%.

economy, it is of importance to study scenarios with lower productivity of capital. This can be done by varying the capital share in the model (through adjusting the parameter β).

Figure 3.4: Economic growth attributed to innovation

Changing the capital share in production has several effects on growth. First, increasing the value for β lowers the market power of monopolies in production, and hence decreases the incentive for firms to invest for further innovation. In the long run, the growth of the economy is lowered since innovation is not encouraged. Second, a higher β implies lower gain from diversification (which is $\frac{1-\beta}{\beta}$). Namely, it lowers the additional growth coming from innovation, so the growth of output is depressed. Third, the economic structure will remain almost unchanged with high β, which is good and bad. It is good because consumers across generations are able to enjoy the same variety of products. It is bad for an open economy, particular for export-oriented economy, because lower innovation means less competitiveness on the global market. Capital can easily flow into countries where the return on capital is high. As shown in Table 3.1, the growth rate of output and consumption decreases with higher β.

We can observe significant structural change for the three scenarios from Figure 3.5. This figure shows the percentage change relative to respective aggregate consumption growth rate. If the value is positive, it means the growth rate of this sector is higher than the average growth rate of the economy, hence the sector is experiencing expansion; if the value is negative, it indicates the sector is shrinking compared to other sectors in terms of GDP share.

Table 3.1: Aggregate effects of innovation on the whole economy with energy policies

β	Reference growth	Aggregate consumption growth	Welfare loss
0.75	1.34%	1.26%	1.1%
0.90	1.25%	1.19%	0.9%
0.99	1.01%	0.97%	0.6%

Note: This table shows welfare loss if energy policies are implemented, compared to the respective baseline scenarios where the growth rate of capital is 1% and $\rho = 4\%$, and absent of energy policies. The only difference among baselines are various values for β.

Figure 3.5: Growth rates of regular sectors relative to aggregate consumption growth rate under different assumption on β

Note: This figure shows relative sectoral growth rates if energy policies are implemented. The respective baseline scenarios assume that the growth rate of capital is 1% and $\rho = 4\%$, and absent of energy policies. The only difference among baselines are various values for β.

Sectors react differently. A drastic change happens in the sector *chm* when $\beta = 0.99$. There is almost no contribution from innovation to the growth of output in this scenario ($\beta = 0.99$). Chemical industry turns from expansion to shrink as the value of β goes up. There are various reasons for this structural change. First, *chm* is an innovative sector which can benefit from substitution of capital for energy and thus the increase in investments. This capital and knowledge intensive feature supports its winning position when β is high, as can be seen in Figure 3.5 when β is 0.75 or 0.90, its growth rate relative to the overall growth rate is extremely high, showing its expanding share in GDP. The benefit from knowledge intensity is diminished when β is 0.99. Second, as the energy policies push forward deeply, the force coming from energy intensity starts to

dominate. Energy intensive sectors decrease significantly when fossil fuel supply declines. We can observe this pattern from sectors such as *agr, oin*, and *trn*. The chemical sector requires both *oil* and *gas* for production. Hence, it will suffer from the decline in fossil fuels. Third, the energy package leads to a substitution between electricity and fossil fuels. The electricity sector expands much faster than in other scenarios. New grids and networks have to be supplemented for larger delivery and storage. The growth of Electricity Transformation and Distribution (ETD) sector demands inputs from other sectors. However, there is no need of input from *chm* according to the Energy IOT, while sectors such as *mch, con, bnk*, and *ose* contribute largely to the production of ETD (the output of ETD can be interpreted as the final delivered electricity). This results in a further decline of output of *chm*. Finally, the linkage between sectors also contributes to the structural change. The output of *chm* is mostly used in the sector *oin* which is also growing much slower in production compared to others. This reduces the demand for *chm*.

The sectoral innovation activity exhibits a similar information as output growth rate. Table 3.2 lists the sectoral innovation growth rate with β equal to 0.90 and 0.99 for five representative sectors. There is a clear indication showing that *chm* turns from the most innovative sector to the least innovative one. This confirms the idea that capital intensity contributes largely to the high growth of this sector. When the innovation is limited due to the available capital, other effects dominate and result in low growth. This table also confirms that the robust growth of electricity sector in the scenario $\beta = 0.99$ where the substitution of capital for energy is restricted. More energy is demanded for growth, while the growth of fossil fuels is limited due to the emission target. This leads to further substitution between electricity and fossils because electricity in Switzerland is CO2 free. These forces together contribute to strong growth in the electricity sectors.

Table 3.2: Growth rate of sectoral innovation (in %)

β	agr	chm	mch	oin	ele
0.90	0.65	0.96	0.89	0.60	0.80
0.99	0.73	0.66	0.87	0.71	0.98

3.4.3   Uncertain perceptions on future generations

One frequently discussed factor which affects the future cost of energy policies is the intertemporal discount rate ρ. In growth theory or in the context of sustainable development, the discount rate is used to reflect the welfare of future generations (or future time periods) in the preferences of the present generation. However, there is no consensus on which value should be used for discounting. The controversial debate on discount rate has led to two opposite opinions. On the one hand, some environmental economists are in favor of low discount rate. One famous example is that Stern (2006) applies

the discount rate of 1.4% for his work "Review on the Economics of Climate Change". Ramsey (1928) also argues that the discount rate should be set close (if not equal) to zero which is "ethically indefensible" for the government to do so. On the other hand, high discount rate are used, typically in the analysis of financial market. Zeldes (1989) has demonstrated that "patience" in consumption is positively correlated with income. In the model, high income is the result of high capital growth. Hence, consumers are more patient when the capital market is booming, where "patient" implies low discount rate for the future. This interpretation allows us to raise the discount rate if low income level (growth of capital) is assumed in our model. Moreover, Weitzman (2001) proposes the so-called gamma discounting, indicating the declining value of discount rate from around 4% per year for the immediate future to around zero for the far-distant future.

The choice of an "appropriate" discount rate to estimate the cost of energy polices has long been a complex decision. In the original model, the discount rate is implicitly set to be 0.74% according to the equation 3.5.[5]

$$\rho = \frac{1+r}{(1+g_Q)^{1-\theta}} - 1, \tag{3.5}$$

where g_Q is the growth rate of output.

Although Stern (2007) prefers the discount rate to be close to zero, Nordhaus (2007) points out that near-zero discounting implies current generations having an unrealistically high willingness-to-pay for reducing damages. This gives problematic results for model simulations with long time horizons (Ramer 2011). Including a time-variant discounting rate will increase the complexity of the model significantly and there will be no BGP in the end. To address this issue, various constant discount rates are included to see the deviation of the model results. Specifically, two extreme values are used for the analysis.

Using IO table with 0.74% discounting rate, the economy can grow at a rate of 1.33% per year when no energy policy is applied. With the shock of exogenous energy policy package, it will suffer from a welfare loss of 1.7% with a lower growth rate of consumption of 1.26%. If we increase the discount rate, the present value of future generations' consumption is lower than before, because later periods have a lower weight in the total welfare. The total welfare loss should thus be considerably lower than before. With a discount rate of 4%, the welfare loss is only 1.1%. The effects on the overall welfare are mitigated with a higher discount rate. However, with the same carbon tax profile, it is not possible to reach the emission reduction target of 65%. A higher tax is required in the future to achieve such emission target, which means the policy cost for achieving the same target is higher with a larger discount rate. On the contrary, if we treat all generations equally,

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[5]The implicit rate of intertemporal pure time preference ρ can also be expressed equation 3.5 according to Rutherford (2004). In the base scenario and previous model version, g_K is equal to 1%, and θ is 0.5, the interest rate is determined to be 1.41% according to the Energy IOT, depreciation rate in the beginning is 4%. This results in a discount rate of 0.74% across generations.

which means to set ρ equals 0, the welfare loss (1.8%) becomes slightly larger due to heavier weights for future generations. In general, the effects on welfare are surprisingly small even though the discount rate varies between 4% and 0. One explanation is that in a dynamic setting, changing discount rate in an economy will also change the interest rate which impacts the investing strategy of asset owners, and finally the output of the sectors.

As shown in Figure 3.6, the results are similar for different discount rates on the sectoral level. This figure includes two energy intensive sectors (*agr, con*), two energy extensive sectors (*chm, mch*) and four energy sectors (*ele, oil, gas, dhe*). There is only a slight change on the sectoral growth rates. The whole structure of the economy will not be affected significantly. With higher discount rate, energy intensive sectors tend to shrink, and energy extensive sectors grow a little faster compared to scenarios with low discount rate. As discussed before, a higher discount rate requires higher tax rate to remain the same climate target. This will increase the price of energy goods and hence reduce the demand for it. Energy intensive sectors will reduce the use of energy goods and hence the output of these sectors will decline compared to before; while energy extensive sectors are now much more beneficial than energy intensive sectors. More inputs flow into energy extensive sectors and make it even cheaper to produce. Finally, the growth rate of energy extensive sectors is higher than before when the discount rate is relatively low. Within the energy sectors, the change in growth rates is the same. The model assumes that the carbon content of *oil* is much higher than that of *gas* and *dhe*. To reach the same level of emission reduction, the reduction in oil consumption is higher than in other energy sectors. Therefore, *oil* sector further decreases and the others raises their outputs.

3.5   Sensitivity analysis

To add some robustness to our computations, a different energy transitions is considered. As estimated by Swiss Cleantech's research (2012), electricity generation from solar energy will double compared to the number reported by Prognos. Instead, other electricity sources contribute with lower market shares in order to keep the total electricity generation be the same level as in Prognos's report. Again, translating the quantity values into market share we obtain a new energy transition path for Switzerland. Figure 3.7 shows the strategy demonstrated by Swiss Cleantech (2012). Electricity generation from nuclear is again phased out gradually. The expansion of hydro technology is limited due to ecological concerns. Renewables are encouraged to develop, particularly the solar energy, it will make up for approximately 35% of the market share in the year 2050.

The aggregate consumption growth rate and welfare level are kept unchanged in the two scenarios. Electricity use grows at the same rate, which allows us to keep the electricity at the same level. Faster expansion in solar energy leads to substitution between electricity generation technologies. Solar is a capital intensive technology which will demand more

Figure 3.6: Growth rates of energy intensive and extensive sectors: scenarios with various ρ

Figure 3.7: Swiss Cleantech's view on future energy transition

capital input for production, compared to technologies such as *hyd, ctp, wel*. For the

electricity sectors as a whole, it requires more capital and less labor or other inputs for production. This increases the relative price for capital and contributes to two effects: the substitution of fossil energy for electricity, and the substitution of labor and energy for capital. Regular sectors which are not capital intensive can gain more growth, for example *agr*, and *con*. All three fossil fuel sectors also have a slower decline due to the substitution effects (Figure 3.8). However, all these changes are marginal.

Figure 3.8: Sectoral growth under different energy transition paths

3.6   Conclusions

In this paper an extended version of the CITE model is used to analyze how an economy accommodates future energy transitions. The Swiss data is used as an illustrative example for a deeper comprehension of the sectoral effects. To answer this question, three aspects have been elaborated in this paper: macroeconomic environment, innovativeness of the whole economy, and discounting future generations.

Historical data and recent studies imply that the capital market of Switzerland is growing steadily at a higher speed than previously assumed. Starting from this point, different growth rates of capital are studied as a driver to describe different macroeconomic environments for Switzerland. The results show that lower capital growth rate tends to develop an economy specialized in capital intensive sectors, while higher capital growth rate can diminish the discrepancy between sectors towards a self-sufficient structure. Moreover, higher capital growth triggers more investment and innovation which can lead

to further growth of the economy. The analysis of historical data shows strong evidence supporting high growth of the economy in the long run. This confirms the robustness of our analysis. To extend these findings to other countries, the government should consider policies to attract capital for sustainable investment if the aim is to sustain the economic structure in the background of energy transition. Otherwise, deep reform of energy sectors can result in dramatic structural change of the economy.

The effects of innovativeness is more complicated because of several forces in play. I find that the chemical sector suffers drastically when innovation is absent. The main reason is that it is a capital and knowledge intensive sector, and benefits hugely from the growth in capital and investment, even though other factors depress its growth. When capital growth is not enough to support innovation, the negative growth effects cannot be offset. The electricity sector, which is not dependent on output from chemical sector, has no negative effects. Factor inputs flow into the electricity sector and contribute to its high growth. The linkage between sectors again pushes the growth of electricity intensive sectors.

The discount rate presents different views on future generations. Under a mild growth of capital (1%), we find that in general the sectoral growth effects depending on how you treat later periods are moderate. However, lower discount rate will result in higher welfare loss because future periods which are heavily shocked by policies have higher weights in welfare. In general, the effects of discounting in dynamic models for analysis in the long-run are not big as one expects. However, such effects can be much stronger of countries with large share of fossil energy uses. For example, China and the US are the two largest emitters using plenty of fossil energies, if substantial emission reduction pledged by the governments, the effects on the economy will be huge. The value of discount rate in such cases can play a significant role in estimating the cost for carbon mitigation. Any policy analysis from such perspective hence should be more careful in picking the discounting values. This is also very important for policy makers to have a more precise understanding the economic cost of long-term energy policies in particular.

The model results are robust when more aggressive renewable expansion is implemented. Sectoral effects on different energy strategies are similar. In general, these results highlight the importance of innovation for the stability of the economy. An energy reform towards expansion in renewables is feasible to achieve with moderate social cost. However, this is the results under a perfect information market where consumers and investors have perfect foresight. Departing from this assumption, drastic energy transition may raise the policy cost significantly. This also illustrates that the government has to create the legal conditions to support a market in the first place, which can solve or partly dissolve the consequence coming from "market failure" which is the common view existing in climate and environmental problems. Otherwise we have to pay for an expensive failure in the future.

It would be interesting to study the issue in the context of varied degree of innovation across sectors. For the current version of the model, the degree of innovation is unique for all sectors which assures all sectors to grow at the same rate in the benchmark absent of policies. This is what growth theory tells us. However, the real world is much more complicated as described in theory. Market structure is different, and the possibility of innovation is varied across sectors. Assuming different rate for innovation can allow us to return to a more realistic world scenario. However, this will increase significantly the problem of model calibration. Moreover, additional data are required to describe the real situation in specific sectors, which may not be easy to obtain. In this regard, this is left for future research.

4 Carbon policy in a high-growth economy: The case of China [1]

4.1 Introduction

China has become the world's largest greenhouse gas emitter: it consumes around fifty percent of global coal extraction and generates eighty percent of its electricity with coal. At the same time, the economic growth of China has been unprecedentedly high, with an average annual growth rate of more than ten percent over the last twenty years.[2] Future climate policies are becoming one of the top priorities for Chinese policy makers as well as for the world community, which is seeking a new international climate agreement.[3]

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

In this paper we develop a multi-sector endogenous growth framework, including energy inputs. We argue that the assessment of climate policies, specifically in a case like

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[1]This chapter represents the joint work with Lucas Bretschger.

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

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

China, is only accurate when we capture economic growth in an appropriate way. We use the well-known increasing-division-of-labor framework developed by Romer (1990) as a theoretical foundation of our model. Here, endogenous innovation and capital investments increase the number of goods varieties and the stock of knowledge, which supports growth by raising productivity. We extend the original theoretical framework to a multi-sector approach with energy and foreign trade; growth of each economic sector is determined endogenously. We then use the framework as a basis for a computable general equilibrium model, i.e. we calibrate the model with Chinese input output data and study the macroeconomic effects of several potential scenarios for future climate policies.

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

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

The paper relates to the literature in three aspects. First, it contributes to the emerging strand of literature on the integration of the *natural environment* into *endogenous growth* theory. Acemoglu et al. (2012) show that the effects and the optimal timing of environmental policy in an innovation-driven growth framework with directed technical change depend on the degrees of substitution between clean and dirty inputs. The effects of carbon policies in our multi-sector approach also rely on inter-sectoral substitution, but contrary to most directed technical change models, we assume economy-wide and not purely sector-specific knowledge spillovers.[4] Bretschger and Smulders (2012) in their theoretical model derive that in a multi-sector economy increasing energy prices do not prevent an economy from having positive innovation and growth even under the conditions of poor input substitution. In a similar way, the present model implements poor input

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

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

In the field of *carbon policy assessment* the importance of China and its climate policy for global greenhouse gases stabilization is eminent.[5] There are various recent contributions on China's climate policy using computable general equilibrium. Huebler (2011) finds that the maximum welfare loss for varying energy policies between 2020 and 2050 in China amounts to four percent. By looking at disaggregated technologies, Dai et al. (2011) argue that China has to decrease coal consumption in the electricity and manufacturing sector in order to achieve the government target of 40-45 percent emission intensity reduction by 2020. Wang et al. (2009) analyze the abatement cost of different Chinese climate policy options and show that absolute emission limits similar to the Kyoto Protocol will seriously impede the Chinese development while the impact of an 80% reduction in carbon intensity by 2050 is relatively small.[6] As reported by Financial Times, Beijing's leading climate economists believe about 7.5 percent of China's GDP in 2030 is likely to be devoted to reduce emissions.[7] These results are related to ours but the main problem with these contributions is that they are based on either static or recursive dynamic models, which do not consider inter-temporal choices. Accordingly, these approaches cannot accommodate forward-looking savings and investment behavior as definitely required by modern endogenous growth theory. To develop a fully endogenous growth model is theoretically and numerically demanding. We show the possibility of constructing such dynamic model and its application to China in the present paper.[8]

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

[6]Further contributions in this context are Zhang (1998), Garbaccio et al. (1999), Liang et al. (2007), and Vennemo et al. (2009).

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

[8]Other fully dynamic CGE models used to evaluate climate policies in a different context are Heggedahl and Jacobson (2011) for Norway and Bretschger et al. (2011) presenting the CITE model for Switzerland; the difference to the latter paper lies in crucial model elements like induced innovation and in the adaptation to specific issues for China like high benchmark growth, special policy targets, and special issues like the effects of urbanization. We present a largely changed version of the CITE model according

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

The remainder of the paper is organized as follows. Section 2 develops the theoretical framework used for the numerical simulation model and derives the conditions for balanced growth. Section 3 describes the data and presents a calibration of the model. Section 4 presents applications of the model and the findings from the model results. Section 5 introduces urbanization to the model and analyzes the reaction of the economy when both fast urbanization and carbon policies are taking place. Finally, section 6 concludes.

4.2 The model framework

4.2.1 Overview

Figure 4.1 shows a diagrammatic sketch of the model. A representative, infinitely lived household supplies primary factors labor (L), research labor (L_R), capital (K), emission permits and other inputs (V). She allocates factor incomes between consumption and investment under perfect foresight in order to maximize intertemporal utility. Emission permits are used in fixed proportion to energy uses based on the carbon content of the different energy sources. In order to obtain the effects of endogenous growth on long-run growth clearly, the baseline model is exempt from distortions, particularly taxes or other policies, as well as spatial considerations related to urbanization. We will distinguish between rural and urban consumers in a separate section. These two types of household are differentiated in terms of consumption preferences. In order to keep the analysis simple, we do not model regionally segmented labor markets; all sectors face the same labor supply.

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to the data availability and economic structure of the country. It covers all important sectors of China's economy.

Figure 4.1: Overview of the model

4.2.2 Growth mechanics

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

$$Y = [\alpha_Q Q^{\frac{\gamma-1}{\gamma}} + (1-\alpha_Q)B^{\frac{\gamma-1}{\gamma}})]^{\frac{\gamma}{\gamma-1}}, \tag{4.1}$$

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

certain point of time, according to:

$$Q = [\int_{j=0}^{J} q_j^{\kappa} dj]^{\frac{1}{\kappa}}, \qquad (4.2)$$

which is the standard extension-in-varieties formulation of new growth theory with $0 < \kappa < 1$. If we assume symmetric intermediate goods, i.e. $q_j = q$, expression (4.2) can be simplified to:

$$Q = J^{1/\kappa - 1} X, \qquad (4.3)$$

where $X = J \cdot q$ measures aggregate input in the intermediate sector. It emerges from (A.2) that output Q can be raised by producing larger quantity per firm q or by increasing the number of varieties (and the number of intermediate firms) J, reflecting the gains from diversification (Dixit and Stiglitz 1977). Specifically, the term $J^{1/\kappa - 1}$ measures the economies of scale on the aggregate level of the economy, because with constant X output increases in J due to increasing specialization of intermediate firms. Intermediate goods q are heterogeneous and thus incomplete substitutes among each other. Hence, each firm j providing q_j operates under monopolistic competition; the term $1/\kappa - 1 > 0$ also corresponds to the optimum markup in the intermediates' sector.

4.2.3 Capital accumulation

We assume each intermediate good needs one capital unit in order to be produced.[9] Accordingly, J denotes not only the total number of varieties and firms but also the amount of capital used in the economy; $1 - \kappa$ represents the share of capital in production. With $g_J = (J_{t+1} - J_t)/J_t$ being the growth rate of capital, g_X the growth rate of intermediate production, and g_Q the growth rate of output we have from (A.2):

$$1 + g_Q = (1 + g_J)^{\frac{1}{\kappa} - 1} (1 + g_X). \qquad (4.4)$$

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

Capital J is accumulated through investments I according to:

$$J_{t+1} = (1 + s)[I_t + (1 - \delta_t)J_t], \qquad (4.5)$$

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

where t is the time index, s the spillover of induced innovation (see next Subsection) and δ_t the depreciation rate. Investments depend on the input of research labor L_R[10] and on other investment specific inputs, B_{inv}, according to:

$$I = [\xi(zJ \cdot L_R)^{\frac{\omega-1}{\omega}} + (1-\xi)B_{inv}^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}}, \tag{4.6}$$

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

4.2.4 Induced Innovation

The hypothesis of induced innovation says that an increase of the price of a specific factor is a spur to innovation increasing productivity via price-induced technical progress. The seminal empirical contribution of Popp (2002) finds strong evidence for induced innovation related to energy use. Jorgenson et al. (2013, p. 481) state that "there is massive empirical evidence of price-induced energy conservation in response to higher world energy prices beginning in 1973" which leads them to conclude that a CGE model dealing with energy necessarily needs to take this into account. Because our general spillover zJ in (4.6) does not change the input-output relations between reference case and policy simulation we need an additional transmission channel for increasing energy prices associated to carbon policies, which we capture with our variable s, see (4.5). Specifically, we assume a positive impact of energy prices on investment productivity according to: 7

$$s = \max[0, \phi(p_e - p_{ref})/p_{ref}], \tag{4.7}$$

where $\phi \geq 0$ measures the impact of energy price p_e on investment productivity s and p_{ref} is the (constant) energy price in the benchmark development, so that $p_e \geq p_{ref}$. We thus assume that higher energy prices, besides having negative effects by reducing intermediate goods production (see next subsection), benefit the economy through positive learning spillovers, increasing the productivity of capital investments and leading to more efficient energy use. Of course, we will carefully calibrate ϕ and test the assumption $\phi \geq 0$ in Eqn. (4.7) for plausibility and robustness under different climate policy scenarios; we

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

also discuss the case $\phi = 0$. In separate simulation we also considered the assumption of s exclusively affecting energy productivity but did not find significant changes in the results. We note that the introduction of spillovers in (4.5) and (4.6) does not create any rents which would violate the usual zero-profit conditions. However, spillovers z and s directly decrease production costs for all the firms, this also leads to accelerating the increase in the number of firms in the intermediate sector, reducing prices to eliminate rents.

4.2.5 Intermediate goods

Intermediate goods q_j are produced using three essential inputs: labor L, energy E, and other input V, which includes the part of capital that is not invested productively (i.e. does not accumulate like the part of capital denoted by J): [11]

$$q_j = J[\varphi L_j^{\frac{\epsilon-1}{\epsilon}} + \xi E_j^{\frac{\epsilon-1}{\epsilon}} + (1 - \varphi - \xi)V_j^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}}, \tag{4.8}$$

with φ, ξ, and $1 - \varphi - \xi$ being the share parameters, and ϵ the substitution elasticity between the three inputs.[12] By multiplying the expression by J, the production of intermediates is assumed to benefit from a knowledge spillover from capital accumulation, which means that the quantity of intermediate goods increases over time with positive investments even when the quantity of the other inputs in (4.8) remains constant.[13]

4.2.6 Energy sectors

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

$$E = [\delta E_{ele}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}} + (1-\delta)E_{fos}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}}]^{\frac{\sigma_{egy}}{1-\sigma_{egy}}}, \tag{4.9}$$

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

In the model, emission is a by-product of the use of energy goods for intermediate

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

[12] L is different from L_R in (4.6) so that there is no labor reallocation between these two labor types with climate policies but our formulation of (4.7) captures a very similar mechanism.

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

production, investment, and consumption. We assume different carbon content for various energy resources used.[14]

4.2.7 Sectors and trade

Below we distinguish twelve non-energy sectors (hereafter regular sectors) and four energy sectors. The output composite B in (4.1) reflects inter-sectoral linkages through the input-output structure of the economy. China trades with the rest of the world (aggregated into one region) on all markets for final goods Y and uses Armington demand functions to model trade, where goods of each sector are differentiated by the region where they are produced. Markets for final goods are perfectly competitive and provide goods for domestic use (D) or exports (P):

$$Y = [\alpha_d D^{1+tr} + (1 - \alpha_d)P^{1+tr}]^{\frac{tr}{1+tr}}, \tag{4.10}$$

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

$$A = [\nu M^{\frac{\eta-1}{\eta}} + (1 - \nu)Y^{\frac{\eta-1}{\eta}}]^{\frac{\eta}{\eta-1}}, \tag{4.11}$$

where ν and $1 - \nu$ are the value shares and η is the elasticity of substitution. We assume that foreign prices are given and asset trade is disregarded in the model, so that goods trade is balanced in each period.[15] In each sector, the market clearing condition requires that supply equals demand.

4.2.8 Welfare and Consumption

Total welfare is derived from individual utilities according to:

$$W = [\sum_0^t (\frac{1}{1+\rho})^t C^{1-\theta}]^{\frac{1}{1-\theta}}, \tag{4.12}$$

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

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

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

(σ_C):

$$C = \left[\zeta C_y^{\frac{\sigma_C-1}{\sigma_C}} + (1-\zeta)C_e^{\frac{\sigma_C-1}{\sigma_C}} \right]^{\frac{\sigma_C}{\sigma_C-1}}. \tag{4.13}$$

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

$$C_y = \prod_{ne} C_{ne}^{\beta_{ne}}, \tag{4.14}$$

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

$$C_e = \left[\iota C_{ele}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} + (1-\iota)C_{fos}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} \right]^{\frac{\sigma_{ce}}{\sigma_{ce}-1}}, \tag{4.15}$$

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

$$C_{fos} = C_{coal}^{\alpha_{coal}} C_{oil}^{\alpha_{oil}} C_{gas}^{\alpha_{gas}}, \tag{4.16}$$

where α_{coal}, α_{oil}, α_{gas} are the respective energy source consumption share in fossil aggregate with $\alpha_{coal} + \alpha_{oil} + \alpha_{gas} = 1$.[16]

4.3 Data and calibration

4.3.1 Input output table

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

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

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

4.3.2 Capital share

An important issue for a dynamic model is the capital share of the economy. Fleisher et al. (2010) find that it is between 0.18 and 0.52, depending on the model specifications. Following Bai et al. (2006), Song et al. (2011) use a value of 0.5 for their numerical studies. These high capital shares are a consequence of the high savings rate but also due to the fact that all these studies do not consider energy as a separate input of production. However, in the input/output data we use it turns out that the energy share of GDP is much higher than in other (developed) economies, at about 20 percent. Furthermore, Bai et al. (2006) find evidence of misallocation of investment in China and an overestimation of capital share in statistics. To reflect the part of less productive capital, we distinguish two types of capital: non-accumulative capital and accumulative capital. Non-accumulative capital enters the production function as an additional input besides labor and energy. Only accumulative capital contributes to the creation of new knowledge. For the accumulative capital we relate to Kuemmel et al. (2002), who estimate an average level of 0.25 for comparable growth miracles such as Japan and Lu and Zhou (2009), who estimate the cost share of capital in the periods 1978-2005 for China to fluctuate between 0.10 and 0.30. Accordingly, we assume the share of accumulative capital to be 0.25 in this study.[17] Because we also include (sector-specific) non-accumulative capital the average capital share of the benchmark economy amounts to around 40 percent on average.

4.3.3 Other assumptions

The prices of all goods are assumed to be constant in the benchmark, which is the usual assumption for CGE models.[18] We will test the impact of increasing energy prices due to increasing scarcities in a separate section below. To determine induced investment reflected in (4.7) we refer to the estimation of Popp (2002) who reports a long run elasticity between 0.354 and 0.421 for (energy-related) technology patents with respect to energy prices. We use a value of ϕ of 0.2 in all the sectors in the first part of the study and test for sensitivity in a separate section below.

Table 4.1 provides the parameter values for the different elasticities we use for numerical simulation. The values are taken from existing studies, specifically van der Werf (2007), Okagawa and Ban (2008), Hasanov (2007), and Donnelly et al. (2004). As customary

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

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

in applied general equilibrium analysis we use economic value flows of the dataset to calibrate the value share and level parameters for the base year of the model. The model is calibrated to a steady-state baseline extrapolated from the base-year IOT with assumptions on growth rate of output, interest rate, depreciation.

Table 4.1: Parameter values for regular sectors and consumption

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

4.3.4 Time frames

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

on the 12th Five-Year-Plan report of the Chinese government, which is our reference to study the carbon policies up to 2020. Two different reference growth rates (4 percent and 7 percent) are used for the analysis of medium run scenarios with a focus on economic effects of carbon policies advocated by the International Energy Agency (IEA). In the long run, the economy is assumed to grow at an average annual rate of 4 percent in the benchmark; carbon policy targets are based on international burden sharing rules which are currently discussed for a global climate agreement. The real interest rate is assumed to be 4% following World Bank data. According to the calibration procedure, the discount rate is implicitly determined by the real interest rate, the reference growth rate of output, and the intertemporal elasticity of substitution.

4.3.5 Benchmark

All policies scenarios are compared to a benchmark. In our multi-sector economy, the benchmark is assumed to be a balanced growth path meaning that all sectors grow at the same steady-state rate; i.e. there is no structural change. The population is assumed to be constant over time (a realistic assumption for China); hence, aggregate work and research labor remain unchanged. The varieties in production expand over time, entailing spillover effects and increasing productivity of intermediate goods' production. According to Equation A.3, an increasing variety of goods (increasing output) can be produced with a given amount of input, which is the source of endogenous growth in our model. In the benchmark, there is no specific investment induced by changing energy prices because these are constant (i.e. $s = 0$). As the carbon contents of energy sources are fixed, emissions grow at the rate of energy and general output in the benchmark.

4.4 Implementing carbon policies

4.4.1 Policy scenarios

China has enacted several national and provincial energy saving regulations and codes to achieve carbon emission reductions. Prominently, the 12th of China's five-year plans for the period 2011 to 2015 aims at an emission intensity reduction of 17% in 2015 against the 2010 value. A long-term target of 40-45% emission intensity reduction in 2020 against the 2005 level has also been specified by the government.[19] These policies will be labeled $CHN40$ and $CHN45$ below. The proposal is less stringent than other countries' announcements such as the U.S. target of a 17 percent reduction of greenhouse gases[20] by 2020 against 2005 because for a fast-growing economy, absolute emissions

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

[20]The target of the U.S. is based on the UNFCCC report. http://unfccc.int/meetings/copenhagen_ dec_2009/items/5264.php.

would still keep growing significantly.

China has recently evaluated the policy of emission cap from 2016 on. But according to the International Energy Agency (IEA 2010), it will likely continue to increase emissions until 2020, emitting 20% more compared to 2010. In the IEA 450 ppm scenario, which we label $IEA450$, (absolute) emissions in China will start to decline only after 2020. Under $IEA450$, total emissions in 2035 are about 71 percent of the 2010 level. The $IEA450$ scenario stops in 2035, but worldwide climate policies are now formulated until 2050. Hence, two scenarios with long term goals will also be considered: $CER524$ and $CER361$. These two scenarios are derived from the contribution of Bretschger (2013). He proposes a general synthetic rule for burden sharing in international climate agreement based on general equity principles, finding that an average budget per capita per year in the period 2010-2050 for China is 5.24 tons in the most favorable case (labelled $CER524$), and 3.61 tons in the most unfavorable case ($CER361$).[21] Considering that Chinese per capita emission in 2010 were 5.4 tons (IEA 2010), total reduction in emissions between 2010-2050 is 3 percent in $CER524$ and 33 percent in $CER361$, respectively. In addition, we study - as a reference policy scenario - a path where the emission level is kept constant at the level of 2010 until 2050 ($ZERO$).

Overall, we evaluate six climate policy scenarios: two government target scenario in the short run ($CHN40$ and $CHN45$); one scenario in the mid-term, namely $IEA450$; two scenarios for the long run, $CER524$ and $CER361$; and, in addition, one scenario for all three time frames with constant emission level over time ($ZERO$). Technically, the emission targets are achieved by imposing carbon taxes for energy use and consumption according to the carbon content of various energy sources. Tax revenues are redistributed to consumers as a lump-sum transfer.

Figure 4.2 depicts the CO2 emission profiles across scenarios in China. As the economy grows at the rate of 7 percent per year, China will emit 14,278 Mt CO2 in 2020, which doubles the 2010 level (7258.5 Mt according to IEA(2010) estimation). For the two government target scenarios, the CO2 emission in 2020 is 10,852 Mt in $CHN40$, and 9,995 Mt in $CHN45$, resulting in a decline in emission by 24 percent and 30 percent respectively compared to the reference scenario. However, this is up to 50 percent increase relative to the emission level in 2010. The absolute emission keeps growing at a relatively lower rate compared to the reference scenario. These two government scenarios allow more emission than $IEA450$ which estimates the emission in 2020 is 9,030 Mt. $CER524$

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

and $CER361$ have the same emission limitation for the year 2020. Before 2020, all the five scenarios have an increase in CO2 emission, showing limited efforts for emission mitigation. The distinction happens after 2020. $IEA450$ requires emissions to go down to 5,164 Mt in 2035, where in $CER524$ 6,097 Mt in 2035 is allowed, 18 percent higher than the level of IEA. The most stringent target is to keep the carbon emission at the level of 3,121 Mt after 2035 in $CER361$, up to 39 percent lower than the IEA level. Table A.1 summarizes all scenarios implemented in this section.

Figure 4.2: CO2 emission trajectories across scenarios

4.4.2 Results of cost estimations

Short run (2010-2020)

Figure 4.3 shows the growth path of aggregate consumption over time across scenarios. Given the high growth rate consumption increases by a factor of two between 2010 and 2020. For the two government scenarios $CHN40$ and $CHN45$ we obtain a growth rate of around 6.91 percent against 7 percent in the benchmark. The discounted welfare loss of the two climate policies is 0.32 percent and 0.34 percent. In scenario $ZERO$, the welfare loss associated with keeping the emission level constant is 0.84%.

Table 4.2: Description of scenarios

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

Medium run (2010-2035)

For the medium run we consider two reference growth rates: 7 and 4 percent. Assuming the 7 percent growth from the short run the welfare loss is 7.23 percent in the $IEA450$ scenario with an average growth rate of consumption at 6.57 percent. As a comparison, to keep CO2 emissions constant (in $ZERO$) the loss in welfare amounts to 5.35 percent. Comparing these results to the short run we find two interesting issues. First, cost of carbon mitigation increases with time, even with the normal assumption of a positive discount rate. The reason is that emission cuts have higher costs with a higher income level. Specifically, in the $ZERO$ scenario it can be seen that the cost of the policy for the first 10 years is 0.84 percent, while the cost for the next 15 years is 4.51 percent. Second, and related to that, it is not beneficial but costly to delay emissions to later periods. The reason is that an earlier redirection of inputs towards investment and growth is beneficial in our growth model. Notably, in $IEA450$, emission reduction mostly happens in the last 10 years (2025-2035) which leads to a substantial increase in welfare cost of carbon policy.

Suggesting that 7 percent annual growth up to 2035 is a too ambitious target we now reduce the reference growth rate of the economy to 4 percent in the baseline. It can be seen from Figure 4.3 that a lower reference growth rate makes it easier for the economy to reach the emission target, as could be expected. Consumption growth in the two policy scenarios is now 3.88 percent. Remarkably, the welfare loss in both scenarios is less than one fifth of the value with 7 percent reference growth (1.34 and 0.94 percent). Hence, even in our endogenous growth model, the cost of carbon emission mitigation increases drastically with the reference growth rate of the economy. There are two reasons for this huge difference. First, a lower GDP growth rate means lower CO2 emissions so that the differences between baseline and emission mitigation targets become smaller. Less resource and effort are required for the emission reduction with lower GDP growth.

Figure 4.3: Annual average growth rates of aggregate consumption under different time horizons

Second, in our fully fledged intertemporal approach, a lower growth rate of the economy implies a higher discount rate[22] which reduces the present value of future cost. As the welfare loss is computed as the accumulative discounted present value over time, the estimated cost is smaller compared to the case of high growth.

Table 4.3: Welfare loss across scenarios with different time frames

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

Long run (2010-2050)

For the long run we assume the reference growth rate of the Chinese economy being 4 percent per year. Enforcing a constant emission level over time (scenario *ZERO*) the growth rate of consumption becomes 3.82 percent, which is somewhat lower than the rate in the medium run. Because development is less dynamic and the time horizon is longer, we obtain a welfare loss of 2.57 percent for this policy. The first case of burden

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

sharing from the global perspective ($CER524$) suggests similar results, the welfare loss amounts to 3.10 percent. $CER361$ showcases the most stringent climate policy scenario. The growth rate of consumption drops to 3.54 percent and welfare loss rises up to 8.33 percent, which is the highest value we obtain in the present setup.

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

4.4.3 Sensitivity analysis

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

Green technologies

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

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

Figure 4.4: Aggregate effects comparison with green technology development in the long run

Results in Figure 4.4 confirm that cost for carbon mitigation can be reduced if renewables are introduced as a substitute for polluting energies. As compared to our previous results, welfare losses decrease in all three carbon policies. The reduction is much larger when technologies such as CCS can be used to decline the carbon content of fossil energies. In the most stringent scenario $CER361$, welfare loss of carbon policy drops from 8.33 percent to 4.5 percent, accounting for approximately half of the total welfare loss. Accordingly, aggregate consumption growth is higher than in the case without a specific technology development.

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

Energy price effects

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

that energy prices increase with the interest rate, i.e. by four percent per year in our numerical simulation.

Figure 4.5: Consumption over time with increasing energy price

As illustrated in Figure 4.5, higher energy price discourages energy consumption and increases prices of consumer goods, especially energy intensive goods. Under such conditions, consumption growth is lower than in the reference case, where energy prices are assumed to be flat. The average short run growth rate of consumption is 6.83 percent (level of reference is 7 percent). Consumption is not very sensitive to the prices in the short run but significant in the longer run, especially in the scenarios with relatively low growth rates of output.[23]

To determine induced investment reflected in (4.7) we refer to the estimation of Popp (2002), who reports a long run elasticity between 0.354 and 0.421 for (energy-related) technology patents with respect to energy prices. As shown in Table 4.4, the positive effect of induced innovation alleviates the negative impact of energy price increase. The positive effect increases in the value of ϕ. So far we have assumed ϕ to be 0.2, the consequences of reducing it to 0 (no learning spillovers from increases energy prices) and doubling to 0.4 are also given in Table 4.4.

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

Table 4.4: Aggregate effects of increasing energy prices with induced innovation

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

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

In absence of induced innovation, the welfare loss of the economy is about 12.44% under the Hotelling pricing assumption. With regard to energy price development, all three long-run carbon reduction scenarios lead to an increase of energy price of more than 4 percent (our Hotelling case), meaning that carbon policies further increase the price of energy. Hence, if we think that Hotelling forces will come into play in the future, the estimated welfare losses above implicitly contain the effects due to the Hotelling price change. It is then illuminating to subtract the effects of the Hotelling energy price path from our estimations.[24] Figure 4.6 shows that, after separating the Hotelling energy price effect, the maximum welfare loss from $CER361$ declines to 6.20 percent. Put differently, the average carbon budget per capita per year in the benchmark has to be around 13.4 tons to sustain annual growth of 4 percent until 2050. The Hotelling energy price path reduces the carbon budget to 7 tons, which accounts for up to 80 percent emission reductions in the carbon policies scenarios. We conclude that in a world with increasing energy prices, emissions will be implicitly reduced through the price effects (both negative price increasing effect and positive price-induced innovation effect), and the required policy efforts to reach long-run emission targets become substantially lower, which also applies to the welfare losses.

Discounting

The choice of the discount rate will affect the estimation in the long run. The model calibration for the above analysis implicitly assumes a discount rate of 1.6 percent in the model. The social planner might prefer a different discount rate to market participants and use a value of 4 percent, which is frequently used in climate policy. Using the reported consumption path from the model and together with the discount rate of 4 percent, the welfare level associated with the new discount rate can be calculated using equation 4.12

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[24]To decompose the effects of induced innovation from aggregate effect in Table 4.4, we assume the (Hotelling) price effect in all three scenarios is the same, the residual between price effect and aggregate effect gives the effect attributed to induced innovation.

Figure 4.6: Decomposition of Hotelling price effect and carbon policy effect

separately. We call this a "static approach" to welfare estimation. The higher discount rate leads to a sharp reduction of welfare loss. The cost of carbon mitigation policy in scenarios $CER524$, $CER361$, $ZERO$ now become 0.81 percent, 3.1 percent, and 0.79 percent, respectively. The reason is that the planner values future consumption losses due to climate policy less than the households.

Instead, a "dynamic approach" analysis is conducted if we impose the higher discount rate to the individuals. The difference between the static and dynamic approach is that interest rate will be adjusted accordingly in a dynamic context. The intertemporal optimization of consumption (Keynes-Ramsey rule) suggests that the market interest rate has to rise as well, in our case from 4 percent to 6.4 percent. The reason is that the benchmark path is determined by a given growth rate. It is then still true that higher discounting reduces the cost of climate policies. But the welfare loss does not decline by a large amount compared to the original estimation since a higher interest rate makes it more expensive to invest in capital and to substitute for fading energy input. This is confirmed by the results from Table 4.5 which shows lower growth rates of consumption in the case of 4 percent discounting compared to the case of 1.6 percent discounting.

Substitution elasticities

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

Table 4.5: Aggregate effects comparison with different intertemporal discounting rates in the long run

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

4.4.4 Results of structural change

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

Figure 4.7: Effects of carbon policies on sectoral growth in the long run

As shown in Figure 4.7, climate policies affect sectoral development. In the general model, technological change and efficiency improvement stem from two substitution effects: (i) substitution between energy input and other inputs (for instance, work labor), because the price of other inputs is relatively cheaper than energy since emission cap implicitly increases the price of energy; (ii) investment in research and the spillover effects from

research labor. Innovative sectors which are capital intensive in the baseline can adjust easier and alleviate the shocks from carbon tax. These two forces come from the setup of the model (see Equations 4.6 and 4.8) and can be observed from the change in the growth rates of regular sectors.

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

As targeted by the policy, the energy sectors suffers from the adopted policies. Within the energy sectors, two substitution effects are effective. The first is substitution between the three fossil energies. Energy sources with higher carbon content can be replaced by sources with lower carbon content since higher carbon content implies that higher tax is imposed for that energy source. It is clear from the figure that coal suffers the most. It shrinks with a rate of between -1.22 percent in $ZERO$ and -4.15 percent in $CER361$, followed by oil, which still grows at a rate of 0.74 percent in $ZERO$ but shrinks with a rate of -1.47 percent in $CER361$. The change of the growth rate in gas is insignificant between $ZERO$ and $CER524$. To achieve the most stringent target in $CER361$, the production of gas has to keep almost at current level. The dependency on natural gas will have to increase since it is relatively cleaner energy source compared to others. The second effect is substitution between electricity and fossil energies. Acceleration of electrification makes it relatively easier to substitute. Specifically in China, substantial investments in power plants and grids construction enlarged the penetration rate of electricity distribution and electric equipment. However, most of the power plants in China are still coal-fired, which means electricity is carbon intensive relative to, for example, gas. This can lead to an "inverse" substitution between electricity and fossil bundles. We can see from the figure that the growth rate of electricity is much lower than two of the three fossil energies in all scenarios. The decline in electricity growth is large. It drops to -0.55 percent in $ZERO$ and -2.68 percent in $CER361$, which provides evidence that the second inverse substitution effect is dominant.

Figure 4.8 offers an overview of the change in energy mix over time across scenarios. $ZERO$ shows a clearly rising share of gas and oil, and a substantially decline in the share of coal and electricity. This result illustrates an induced transition towards cleaner energy sources when climate policy is binding. The sub-figure in the bottom right illustrates the correlation between energy consumption and CO2 emission. With the emission reduction, total energy consumption also declines.

Figure 4.8: Change in energy mix in different policy scenarios

4.5 Urbanization and sectoral change

As predicted by the United Nations (2013), by 2050 total population in China will remain almost at today's level[25], even though it first increases to peak around 2025 and declines afterwards. The most dominant demographic effect is urbanization. The rate of urbanization is seen as a sign of success of economic achievement. China's population urbanization rate in 2010 reached about 50 percent from 10.6 percent in 1949, showing a significant urbanization development process over time.[26] It is predicted to further climb to near 60% in 2020 and around 66% in 2030.[27] We explore the long-run effects of urbanization on sectoral growth in this section.

Depending on the region where one lives, people have different consumption bundle preferences, which are reflected by parameters in consumption equations.[28] The urbanization rate is exogenously given in the model for simplicity.[29] We assume the urbanization ratio

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

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

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

[28]Explicitly, ζ in equation 4.13, β_{ne} in equation 4.14, ι in equation 4.15, and α_{coa}, α_{oil}, α_{gas} in equation 4.16 are distinguished between regions according to Input-output table data calibration.

[29]The government is expected to be careful when allocating fiscal spending as it carries out the new urbanization plans. One precondition for urbanization should be ensuring a sufficient and stable supply of

increases to 60 percent in 2020 and continues to rise up to 66% in 2030 (hereafter URB). The rate of urbanization in 2050 will reach 78 percent, converging to current level of US.

When people move from rural to urban regions as predicted, total rural consumption growth declines from 4 percent to 1.10 percent in the reference case, while total growth of consumption in the cities increases to 4.36 percent. Data in the base year show that people living in cities consume more than rural residents. Hence, welfare of the whole economy increases with the urbanization process (by 0.1 percent).

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

Figure 4.9: Growth rates of sectors with urbanization development

Table 4.6 provides the results when carbon policies ($CER524$, $CER361$ and $ZERO$) are

agricultural produce, which will require improved efficiency in agricultural production, based on advanced technology and management. In addition, the provision of housing, social security and education for migrant workers and their children once they settle in the cities, will also present problems that must be solved during the urbanization process.

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

Table 4.6: Consumption growth rate and welfare loss when climate policies areimposed

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

Table 4.7: Growth rate of sectors in the long run (in %)

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

Sectoral diversification follows the similar patterns as described in the last section. Energy intensive sectors decrease relatively more while labor capital intensive sectors are able to adjust and alleviate the effects of climate policies. When urbanization is taking place, sectoral growth changes slightly. As shown in Table 4.7, sectors which produce goods that are more demanded by urban household, such as *mch, con, gse, wat*, grow at a higher rate, while the growth rates of other sectors (e.g. *agr*) decline.

4.6 Conclusions

Using a multisector endogenous growth model, the paper derives the costs of carbon policies in China. We argue that growth dynamics constitute the crucial model element

permitting reliable calculation of the effects. Intersectoral linkages and spillover effects are also important drivers of macroeconomic development. Capturing the energy sector, with energy as an essential input to production in different sectors, in an accurate way is crucial for the results. More detailed modeling of the interaction between energy input and economic growth results in a more precise estimation of the cost of climate policies.

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

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

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

5 Knowledge diffusion, economic growth and climate policy: A global perspective

5.1 Introduction

Economic growth is driven by the accumulation of capital stocks. In closed economies, domestic capital build-up determines the growth rate of the economy. Accordingly, the growth effects of environmental policies can be obtained by looking at the effects on domestic capital accumulation. In open economies, the transboundary exchange of capital has an additional effect on the regional growth. There are mainly two reasons to focus on knowledge capital in this context. First, international transmission of knowledge is inexpensive and not bounded by market operations. Second, marginal returns are often assumed to be constant for knowledge but decreasing for physical capital; under these assumptions it is knowledge accumulation that determines long-run development. As a consequence, when one evaluates the effects of global policies such as climate policies, induced changes in international knowledge transmission become important. Climate policies could induce additional knowledge creation and diffusion, counteracting the negative cost effects of higher energy prices. But this has to be verified quantitatively, applying a well-specified framework on economic growth and knowledge, to which this paper addresses.

This paper is related to several different strings of literature. In addition to the endogenous growth and innovation literature (e.g. Romer 1990), there are now several complementary frameworks for the modeling of knowledge diffusion. These can be classified into three groups. The first one includes econometric analysis of the technology diffusion and adoption in selected firms or industry. This group of studies tries to identify the channels where the knowledge spillover takes place. For instance, Coe and Helpman (1995), Coe et al. (1997), Keller (1998, 2004), and Lumengan-Neso et al. (2005) find evidence that knowledge spillover is associated with trade. The second group includes a series of papers focusing on theory models. Markusen (2002), Rodriguez-Clare (1996), and Fosfuri et al. (2001) state that knowledge spills over through patents sharing among multi-national

firms and is linked to foreign direct investment. The final group aims to identify the factors that impact the diffusion of knowledge and their relationship with growth. Nelson and Phelps (1966) study the connection between technological diffusion and economic growth in general. Acemoglu et al. (2012) emphasize on the role of standardization in innovation and growth.

The emphasis of this paper is on the general equilibrium effects of different channels of knowledge spillovers, which complements all the above mentioned groups of papers. This analysis bridges the theoretical papers that study the modeling approaches of knowledge diffusion and empirical literature focusing on identifying the size of knowledge diffusion. We extend the literature in a number of important ways, in particular by introducing explicit knowledge spillover into knowledge production function. Within the expansion-in-varieties growth framework, we are able to identify contemporaneous knowledge diffusion from intertemporal knowledge spillover. Some of the findings in this paper may be missing in a partial equilibrium framework.

Finally, this paper is also related to the literature on economic effects of climate policy. Most of the studies on climate policy utilize the standard classical growth model and assume no or limited knowledge diffusion. Bosetti et al. (2008) include the energy related technology diffusion to a CGE model with some crude assumptions on the elasticities. Carbone et al. (2009) evaluate the efficacy of international trade in carbon emission permits and they find that smaller groupings perform better than agreements with larger groups. Bretschger and Smulders (2012) derive that in a multi-sector economy increasing energy prices do not prevent an economy from having positive innovation and growth based on a theoretical model with endogenous growth (or say, with inter-temporal knowledge spillover). The strength of this paper is that, first the growth is powered through innovation in knowledge, and second all parameters associated with knowledge diffusions are estimated carefully through patent and citation data. This paper complements to the literature by constructing a multi-region-multi-sector endogenous growth model with full capacity in chasing the knowledge diffusions across regions.

This paper is organized as follows. Section 2 is a detailed literature review of current studies on knowledge spillover and modeling approaches. Section 3 describes how the knowledge spillovers are included in the endogenous growth model, and other conditions on the international trade and for the model closure. Section 4 explains the econometric strategies used to estimate the knowledge related parameters and elasticities used for model estimation. Section 5 presents and discusses the results and findings. Section 6 concludes the paper.

5.2 Literature review on modeling spillovers

Griliches's contribution (1979) is one of the first papers addressing two types of spillovers: the embodied knowledge spillover[1] and dis-embodied knowledge spillover. The embodied knowledge spillover is what he called "rent spillover", which is due to the fact that purchase prices of imported goods do not reflect their "full quality price" including the opportunity cost of R&D of foreign innovation. Since during the production of intermediate goods the monopolistic competition characteristics of individual firms allows them to charge a price premium, part of the embodied knowledge spillover effects is absorbed through the mechanism and spreads to other regions and/or sectors with trade and inter-sectoral linkage. The dis-embodied knowledge spillover refers to borrowing ideas by industry s from the research results of industry r. Usually both types of knowledge augment domestic knowledge stock while the learning cost is lower than the original R&D cost. We consider the dis-embodied spillover only in this paper.

Keller (2004) identifies two channels for embodied knowledge spillover: trade and FDI. As for trade, both importing and exporting activities may lead to spillovers. Coe and Helpman (1995) relate TFP to domestic and foreign R&D, and find a positive and quantitative large effect from import-weighted foreign R&D. Similar results are found in Coe, Helpman and Hoffmaister (1997). Keller (1998) uses randomly created shares instead of import shares in Coe and Helpman (1995), and finds same implication for Coe, Helpman and Hoffmaister (1997).[2] Furthermore, Lumenga-Neso, Olarreaga, and Schiff (2005) capture the "indirect" trade-related spillovers[3] and claim this as a better estimation than the work of Coe and Helpman (1995) and Keller (1998). There are also some articles concerning exporting related spillovers. According to the results from econometric analysis in these literature, Keller (2004) concludes that importing is associated with spillover while empirical evidence on learning effects from exporting is not as clear cut as stated in the literature.

Foreign direct investment (FDI) is also considered as an important channel for knowledge spillover. Theoretical papers (Markusen 2002; Rodriguez-Clare 1996; Fosfuri et al. 2001) support this idea by stating that externalities of knowledge can be transferred through parents sharing in MNEs (multinational enterprises), labor training, turnover, or provision of high-quality intermediate inputs. Both analyses at the manufacturing level and micro (firm or plant) level[4] show the positive relationship between FDI and productivity growth.

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[1]Embodied knowledge spillover has its origin from the empirical work of Coe and Helpman (1995). This type of spillover is embodied in the flow of physical commodities transactions through the channels of trade and FDI.

[2]Keller (2000) finds that "random" import shares perform as well as actual import shares by using industry level data for G-7 countries plus Sweden. Keller (2002) provides evidence in the industry level that bilateral trade flows are the main channel of transmission of international knowledge.

[3]"Indirect" means that knowledge spills over to country A through importing from country B is not only associated with the knowledge stock of country B, but also the spillovers to country B from C through the trade between B and C.

[4]Earlier literature concluded that there was no evidence of FDI spillovers, however recent studies

There are two distinctive features for the FDI-associated spillovers: a) high-tech industries have stronger spillovers than the low-tech industries[5]; b) rich countries can benefit more from FDI spillovers than poor countries.

Stiglitz (1999) argues that knowledge is rather a global public good instead of simply a public good. New knowledge, mostly advances on basic knowledge can be conveyed worldwide by a printed article instead of being embodied in a particular product, which delivers a non-pecuniary externality (Griliches 1992). Flow of new knowledge such as information and ideas contributing to a single worldwide research sector has growth effects (Rivera-Batiz and Romer 1991). Adam (1990) proposes the concept of "learning pools" for industries which are consist of findings from basic research and are available for all firms. He also finds large effect on productivity due to knowledge absorption, however this effect is time lagged. These articles illustrate the existence of a "knowledge pool" as a channel for knowledge spillovers.

In general, the knowledge spillovers are a function of the total available knowledge and the spillover coefficient[6], as described in the following equation:

$$H = \alpha \cdot S, \tag{5.1}$$

where H is the knowledge spillover, α is the so-called spillover coefficient, and S is the total available knowledge stock outside of the firm (or industry, sector, region, country, etc). Both α and S can be defined using various proxies. Following are the mostly used measures of "proximity".

5.2.1 Distance to technological frontier

Bosetti et al. (2008) apply the explanation from Gerschenkron (1962) and Rosenberg (1994) to formulate the technological frontier (international knowledge pool), which they describe as the sum of the stocks of R&D capital detained by high income countries.

$$S(i,t) = \sum_{j \in hi} N(j,t) - N(i,t), \tag{5.2}$$

where $N(i,t)$ is the stock of knowledge in sector i. Furthermore, they define the spillover coefficient by the relative distance of technology in sector i:

$$\alpha(i,t) = \frac{N(i,t)}{\sum_{j \in hi} N(j,t)}. \tag{5.3}$$

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contradicted previous results and estimated economically large spillovers from FDI.

[5]This means only some forms of FDI in certain sectors can deliver externalities of knowledge.

[6]It is a form of absorptive capacity, however, I will use the term "absorptive capacity" for something really related to "absorption". Hence, I define the term "spillover coefficient" here instead.

Hence,

$$H = \frac{N(i,t)}{\sum_{j \in hi} N(j,t)} \left[\sum_{j \in hi} N(j,t) - N(i,t) \right]. \tag{5.4}$$

5.2.2 Similarity between firms

Jaffe (1986) suggests the uncentered correlation approach to measure the technological distance. He uses the patent citation data to define patent distribution vector F whose elements are the fractions of firm i's research efforts in various fields. Then the distance of technology between two firms can be defined as follow:

$$\alpha(i,j) = \frac{F_i F_j'}{[(F_i F_i')(F_j F_j')]^{1/2}}, \tag{5.5}$$

where $0 < \alpha < 1$. α close to unity means that the two firms have a large degree of overlap between their research interests. The spillover into sector i is:

$$H_i = \sum_j \frac{F_i F_j'}{[(F_i F_i')(F_j F_j')]^{1/2}} \cdot N_j. \tag{5.6}$$

Lane and Lubatkin (1998) test the relative similarity of firm level characteristics, and find positive relation between similarity and the relative ability to obtain knowledge. Adams[7] (1990), Branstetter (2001) and Acemoglu et al. (2007) use this approach to investigate technology diffusion in the firm level.

5.2.3 Euclidean distance

Inkomann and Pohlmeier (1995) propose the following approach to measure the technological distance:

$$\alpha = \sqrt{\sum_{p=1}^{P} (\frac{x_{ip} - x_{jp}}{S.D.(x_p)})^2}. \tag{5.7}$$

The vector x_p includes P elements which can be firm size, demand expectations, sectoral affiliation, etc. This approach is able to capture two features: a) frontier firms may be easier to extract other's knowledge; b) laggard firms may gain much more than others.

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[7]Adams uses data on firms' shares of scientists in each of its k fields of science. While Jaffe uses patent citation data.

5.2.4 Trade intensity

As for spillovers through the channel of knowledge pool, Mancusi (2008) uses the above mentioned equation, and calculates the spillover coefficient α as the percentage R&D stock generated in sector i. He also identifies national spillovers and international spillovers by the sourcing countries of R&D.

In terms of spillover through trade, the spillover coefficient is a function of trade-related variables. Lichtenberg and van P. Potterie (1998) use the fraction of foreign country's output that is exported to the home country as the spillover coefficient[8]. Leimbach and Baumstark (2010) define the trade-related spillovers by introducing the term "trade intensity":

$$H = \left[\frac{X(j,t)}{K(j,t)}\right]^{\phi} \iota[(N(j,t) - N(i,t))], \tag{5.8}$$

where $\frac{X(j,t)}{K(j,t)}$ is the ratio between imported capital and the domestic capital stock, $\phi < 1$ shows a decreasing marginal spillover effect of capital exports, and ι is the spillover intensity.

De Cian and Parrado (2012) define the spillover coefficient as:

$$\alpha = \alpha_0 CS \cdot CR \cdot MS, \tag{5.9}$$

where CS, CR, MS are different shares reflecting the characteristics of imports, and α_0 is a constant.

5.2.5 Institutional effect

Coe, Helpman and Hoffmaister (2009) revisit the work of Coe and Helpman (1995) and introduce institutional variables to examine the impact on spillovers. Their results suggest that institutional differences are important determinants of productivity and that they impact the degree of R&D spillovers. Their findings can be interpreted with following equation:

$$H = \beta m N, \tag{5.10}$$

where β is the institutional effect and m is the share of imports in GDP.

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[8]They examined the FDI by substituting bilateral measures of FDI instead of imports in Coe and Helpman (1995).

5.3 The multi-regional model with knowledge spillovers

In this section, we present the baseline model. This is a dynamic general equilibrium model where the whole world economy is composed by several regions. In each region of the model, the final output combines sectoral specific inputs using intermediate aggregates and general inputs. Capital, labor, energy and knowledge are used for intermediate aggregate production under monopolistic competition where individual firms earn positive profit to cover their fixed cost. Production is subject to taxes, so that profit-maximizing decision making firms will reallocate capital investments for improving productivity and alleviating the impacts of taxes. Research in the model is directed for the expansion in varieties which enable new firms to entry into production. External knowledge spilled over into the industry provides extra productivity increase for the whole sector. Such positive externality spreads to other sectors and regions through cross-sector interaction and international trade. The following describes the new modules of the model.

5.3.1 Knowledge spillover

The seminal work of Rivera-Batiz and Romer (1991) suggests that economic integration increases the worldwide stock of ideas, and hence contributes to the growth. We borrow this idea for the construction of knowledge pool in our model. However, knowledge itself, particularly tacit knowledge, is unmeasurable, and its flows are invisible (Krugman 1991). This means that studying knowledge spillovers quantitatively have to rely on crude proxy variables. In general, new knowledge stock of sector a is a function of the existing knowledge stock $J_a(t)$ and an augmenting component due to spillover effects $\tilde{J}_a(t)$.

$$J_a(t+1) = J_a(t) + \tilde{J}_a(t), \tag{5.11}$$

where $\tilde{J}_a(t)$ is defined by accessible knowledge from other sectors or regions presenting the "absorptive capacity" of specific sector φ_a and the production elasticity reflecting the transformation of the absorbed knowledge into new varieties μ. If assuming the world consists of only two regions a and b, and each region has only one sector, the spillover effects of region a can be expressed as follow:

$$\tilde{J}_a(t) = [\sum_{b,b\neq a} \varphi_a J_b(t)]^\mu. \tag{5.12}$$

Many factors can affect the size of φ_a, for instance, the cultural difference, geographic distance, trade treaties between regions, the level of knowledge in the world technology ladders. The size of knowledge stock at home country is one of the factors that impacts the value of μ. Further discussion and estimation of the two will be presented later.

To extend our analysis to multi-channels, we assume each of the regions has two sectors

s and r. By distinguishing the sourcing sectors of spillover, we can identify four channels of spillovers: intra-sectoral spillovers domestic, inter-sectoral spillovers domestic, intra-sectoral spillovers foreign[9], inter-sectoral spillover foreign[10]. All the four channels are the so-called contemporaneous knowledge spillovers. As for intra-sector spillovers domestic, as it is almost fully accessible for all firms, the value of φ in this type of spillover is 1. However, as the inter-sectoral spillover foreign is rare and hard to identify from the availability of data, we assume the accessibility is zero. Hence, we exclude this channel, and only consider the rest of the three together with the intertemporal knowledge spillover.

Table 5.1: Four types of contemporaneous knowledge spillovers are possible in theory

	Intra-sectoral	Inter-sectoral
Domestic	A	B
International	C	D

The "expansion-in-varieties" mechanism captures the intertemporal knowledge spillover which is different from the four channels of contemporaneous knowledge spillovers described above. We refer to contemporaneous knowledge spillover if without further indication in the paper. Hence, equation 5.11 can be further expanded as follows:

$$J_{s,a}(t+1) = J_{s,a}(t) + \tilde{J}_{s,a}(t)[\tilde{J}_{r(r\neq s),a}(t)][\tilde{J}_{s,b}(t)], \tag{5.13}$$

where $\tilde{J}_{s,a}(t)$ is the intra-sectoral spillover within the same region (Type A); $\tilde{J}_{r(r\neq s),a}(t)$ is the inter-sectoral spillover within the same region (Type B); $\tilde{J}_{s,b}(t)$ is the intra-sectoral between regions (Type C). More parameter estimations are required to capture the differences between channels using equation 5.13.

5.3.2 Open economy and trade

It is assumed that trade between any pair of regions is possible. In each region, the produced final goods are consumed by domestic household or exported to other regions. Output composite B in equation 4.1 reflects inter-sectoral linkages through the input-output structure of the economy. Each region trades with the rest of the world (all the other regions abroad) on all markets for final goods Y. For simplicity Armington demand functions are employed to model trade, where goods of each sector are differentiated by the origin region of production. Markets for final goods are perfectly competitive and provide goods for domestic use (D) or exports (P):

$$Y = [\alpha_d D^{1+tr} + (1-\alpha_d)P^{1+tr}]^{\frac{tr}{1+tr}}, \tag{5.14}$$

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[9]Knowledge spillovers from foreign countries of the same sector.

[10]Knowledge spillovers from foreign countries of other sectors.

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

$$A = [\nu M^{\frac{\eta-1}{\eta}} + (1-\nu)Y^{\frac{\eta-1}{\eta}}]^{\frac{\eta}{\eta-1}}, \tag{5.15}$$

where ν and $1-\nu$ are the value shares and η is the elasticity of substitution. The total import in sector s of region b ($M_{s,b}$) is a CES aggregation of goods imported from all the other regions plus the transport margins

$$M_{s,b} = [\sum_{a,a\neq b} \psi_{s,a,b}(M_{s,a,b} + TN_{s,a,b})^{\frac{\sigma_M-1}{\sigma_M}}]^{\frac{\sigma_M}{\sigma_M-1}}, \tag{5.16}$$

where $\psi_{s,a,b}$ is the share of import from a in total imports with $\sum_a \psi_{s,a,b} = 1$. $TN_{s,a,b}$ is the value of transportation services needed to transport goods $M_{s,a,b}$ from region a to region b.

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

$$\sum_{a,b} p^M_{s,a,b} M_{s,a,b} = \sum_{a,b}[p^{EX}_{s,a,b}(1 + t^{ex}_{s,a,b})EX_{s,a,b} + p^{TR}_{s,a,b}TN_{s,a,b}](1 + t^M_{s,a,b}), \tag{5.17}$$

where $p^M_{s,a,b}$ is the price of import, $p^{EX}_{s,a,b}$ is export price net tariff, $p^{TR}_{s,a,b}$ is the unit cost of transportation service, $t^{ex}_{s,a,b}$ and $t^M_{s,a,b}$ are the export and import tariff.

5.3.3 Current account balance

In the model, the equilibrium condition requires that the present value of consumption is equal to the present value of income over the entire time horizon. This is the budget constraint which has to be held. However, a region is able to borrow or lend money in a given time period t, which is the so-called current account surplus or deficit. As stated in Carbone et al. (2003), the closure of financial flows within the model needs an additional constraint on current account deficit for the whole world. That is, for any given time period, the "global" current account deficit has to be zero.

$$\sum_a CA_a(t) = 0. \tag{5.18}$$

Springer (1999) and Rutherford (2003) defines that the current account of a region as the trade deficit, which means if one country imports more than its exports (in terms of

value), it will result in current account deficit.[11]

$$CA_a = \sum_{s,b} p_{s,a,b}^{EX} EX_{s,a,b} - \sum_{s,b} p_{s,b,a}^{M} M_{s,b,a}. \tag{5.19}$$

The closure of financial flow is determined by fulfilling the budget constraint 5.20:

$$w(t)^U L_U + w(t)^R L_R + \sum_f p(t)^f E_f + r(t)A(t) \geq C(t) + \dot{A}(t) + CA(t), \tag{5.20}$$

with transversality condition holds to avoid Ponzi game. Here $w(t)^U$ and $w(t)^R$ are the wage rates of production and research labor, $p(t)^f$ is the price of resources including natural resources and price of permits of carbon policies are implemented, E_f is the endowment of resource f, $r(t)$ is the equilibrium interest rate on assets $A(t)$. $CA(t)$ is the current account deficit in time t which will be discussed later.

The condition given by equation 5.19 also closes the model.

5.3.4   Data

The dataset used for the model is GTAP 8, and this paper follows the rules developed by Rutherford (GTAPinGAMS model) for data aggregation before the model calibration. GTAP 8 Data Base[12] is used to analyze the effects of energy policies on economic growth.

This analysis focuses on the major players in the world, in terms of economic significance and impacts of world emission from the perspective of carbon mitigation. We aggregate the data into seven regions, namely Europe (EUR), the United States (USA), Russia (RUS), China (CHN), India (IND), List of Annex A countries of the Kyoto Protocol (RA1), and the rest of the world (ROW). According to the data availability, sectors are assembled into following categories to reflect the major sources of carbon emissions in economic activities, which are agriculture (agr), transportation (trn), energy intensive production (ein), manufacturing (man), electricity (elec), coal (coa), oil (oil), gas (gas), and other residual sectors (ors)[13].

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[11]Since in the model the balance of trade deficit or surplus holds for any given time, the total value of export equals the total value of import for the whole world. the world balance of current account (5.18) holds automatically by such definition.

[12]More information on this data set can be found on the web-page: https://www.gtap.agecon.purdue.edu/databases/v8/.

[13]Most of the sectors in this group are the service sectors such as banking, insurance, telecommunication, hotel, etc. There is no data available to identify knowledge spillover in these sectors.

5.4 Econometric estimation

This section includes the economic strategies employed to estimate all the necessary parameters and elasticities for our quantitative model. The empirical foundation of knowledge diffusion is based on patent and citation data. These data are obtained from OECD, which covers a wide range of regions and sectors.

5.4.1 Statistical identification of parameters

The empirical analysis[14] is divided into two parts. First we determine the parameters related to knowledge flows (φ_a) and in the second part we use the model specification 5.13 to estimate elasticities in knowledge production. Usually equation 5.13 is directly transferred into a linear regression where the $J-$variables are approximated by accumulated R&D investments (e.g. Keller 2002). Innovative output is typically approximated by the patent count from the corresponding regions and sectors. Our specification includes both inter-regional and inter-sectoral spillovers.

In a first step we examine the empirical characterization of the φ_a-parameters. Accessibility to external knowledge stock is not homogeneous, which is studied in literature as localization of knowledge spillover (Jaffe et al. 1993; Jaffe and Trajtenberg 1996, 1999; Maurseth and Verspagen 2002; Peri 2005). Following Caballero and Jaffe (1993) and Peri (2005), we may interpret the φ_a-parameters as the probability that an idea generated in an external sector or region is accessible by the receiving sector and/or region. The accessibility will depend on the characteristics of the corresponding regional and sectoral couples. Thus, in the empirical specification φ_a will be represented as a function of z_{ij} which reflects potential resistance factors between the regions and sectors. Then we can regress the share of idea generated in the corresponding external region or sector on these resistance factors. As in Peri (2005), the model specification is:

$$\varphi_{ij} = \exp[a + z_{ij}'b], \tag{5.21}$$

where z_{ij} is a vector of trade flows and different types of fixed effects (industry, country, etc.) related to the knowledge producing and knowledge receiving region and country. a and b are the estimated parameters.

In the second step, we estimate the effect of accessible external knowledge on the own innovation output based our extended knowledge production function. These parameters can be then interpreted as the elasticities of knowledge production with regard to different

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[14]This econometric estimation is a joint project with Filippo Lechthaler. I thank Filippo for extensive help in estimating the parameters used for the CGE model.

knowledge stocks.

$$\frac{J_a}{(\varphi_a J_b)} \frac{d(\varphi_a J_b)}{dJ_a} = \mu. \tag{5.22}$$

5.4.2 Data and measurement

The citation between patents is a usual proxy applied to represent the diffusion of ideas through learning. According to Peri (2005) a citation informs us that the researcher knows about an existing idea and that the idea has some relevance in the research process. The number of citation links between regions as well as the number of international patent applications are available from the World Patent Statistical Database (PATSTAT) and OECD Patent Citation Database.

We approximate the knowledge stocks J based on accumulated yearly patent applications:

$$J_{a,s,t} = D_{a,s,t-1} + (1 - \delta)J_{a,s,t-1}, \tag{5.23}$$

where $D_{a,s,t-1}$ is the patent application data for region a, sector s and time $t-1$.

Then we use patent citation data to calculate weights φ-parameters. Take the estimation of parameters for spillover B as example. Assume that $\varphi_{a,s,r}$ is the accessibility of the knowledge stock in sector r from sector s within region a, $c_{a,s,r}$ is the number of citations from patents classified into technological field s to patent classified into technological field r within region a, we can have the relative frequency to be:

$$\varphi_{a,s,r} = \frac{c_{a,s,r}}{\sum_r c_{a,s,r}}. \tag{5.24}$$

We further control citation data for "confounding" effects by considering the trade and size effects. Table 5.2 provides the weights of accessibility intensity of type B spillover for the region EUR. The other estimated parameters can be found in the appendix. There is no data available to identify knowledge spillover in sector ors, col, oil, gas, cru. Hence, we assume that the weights for sector ors is zero as services aggregated into ors is hardly possible to identify spillovers; sectors col, oil, gas, cru have the same weights as sector ele as they all belong to energy sectors and share similar characteristics.

Finally we can obtain the accessible external knowledge stock measured as a weighted sum of all relevant knowledge stocks in all regions as in equation 5.25. The accessible external knowledge stock for the channel C (J^C) can be estimated following similar steps. Table 5.3 gives the weights of accessibility intensity of type C spillover for the region

Table 5.2: Calculated weights representing the accessibility intensity for region *EUR*

	agr	*trn*	*eis*	*man*	*ele*
agr	-	0.05	0.95	0.01	0
trn	0	-	0.67	0.14	0.19
eis	0.11	0.60	-	0.04	0.25
man	0	0.55	0.29	-	0.16
ele	0	0.30	0.60	0.10	-
ors	0	0	0	0	0
col	0	0.30	0.60	0.10	0
oil	0	0.30	0.60	0.10	0
gas	0	0.30	0.60	0.10	0
cru	0	0.30	0.60	0.10	0

Table 5.3: Calculated weights representing the accessibility intensity of Type C spillover for region *EUR*

	EUR	*USA*	*RUS*	*CHN*	*IND*	*RA1*	*ROW*
agr	-	0.19	0.09	0.22	0.24	0.18	0.08
trn	-	0.19	0.14	0.14	0.21	0.18	0.15
eis	-	0.18	0.13	0.18	0.18	0.17	0.16
man	-	0.17	0.15	0.17	0.22	0.16	0.13
ele	-	0.19	0.13	0.17	0.16	0.19	0.16
ors	-	0	0	0	0	0	0
col	-	0.19	0.13	0.17	0.16	0.19	0.16
oil	-	0.19	0.13	0.17	0.16	0.19	0.16
gas	-	0.19	0.13	0.17	0.16	0.19	0.16
cru	-	0.19	0.13	0.17	0.16	0.19	0.16

EUR. See the appendix for the estimated results of other regions.

$$J_{a,s,t}^{B} = \sum_{r \neq s} \varphi_{a,s,r}^{B} J_{a,r,t}. \tag{5.25}$$

The next step is to estimate the elasticities for knowledge production. As the frequencies of patent applications from each regions over time and technologies follow the pattern of Poisson distribution. We therefore can estimate the elasticities in the Poisson regression context.

$$\tilde{J}_{a,s,t} = \exp(\beta_{s2} J_{a,s,t} + \beta_{s3} J_{a,s,t}^{B} + \beta_{s4} J_{a,s,t}^{C}), \tag{5.26}$$

where parameter $\beta_s = (\beta_{s2}, \beta_{s3}, \beta_{s4})'$ is based on a Poisson regression. Other than in the linear model, the marginal effect of J_a on $\tilde{J}_a$ is not constant. It depends on the level of J_a (See equation 5.27). The value of β_s can be interpreted as approximately $100 \cdot \beta_s \%$ change in $\tilde{J}_a$ with a unit change in J_a.

$$\frac{\partial E(\tilde{J}_a | J)}{\partial J_a} = \frac{\partial \exp(\beta_s J_a)}{\partial J_a} = \exp(\beta_s J_a) \beta_s. \tag{5.27}$$

With the estimated β_s we can derive the elasticities $\alpha_s = (\alpha_A, \alpha_B, \alpha_C)'$ in terms of average effects. Assume $1/\bar{J}_a$ is the average relative value of a unit increase of J_a, the implicit elasticities are expressed as follows:

$$\frac{J_a}{\tilde{J}_a}\frac{d\tilde{J}_a}{dJ_a} = \beta_s \bar{J}_a = \alpha_s. \tag{5.28}$$

The concept of elasticities in the knowledge production function helps to bridge the gap between the different functional forms of the spillover process in the numerical growth model and the empirical specification. Table 5.4 shows the derived elasticities in sectoral level and their mean values (disregard of regions).

Table 5.4: Elasticities of transforming external accessible knowledge into new knowledge stock

Sectors	α_A	α_B	α_C
agr	0.09	0.26	0.04
trn	0.33	0.23	0.10
eis	0.40	0.19	0.17
man	0.32	0.23	0.11
ele	0.16	0.23	0.08
ser	0.00	0.00	0.00
col	0.16	0.23	0.08
oil	0.16	0.23	0.08
gas	0.16	0.23	0.08
cru	0.16	0.23	0.08
mean	0.26	0.23	0.10

5.5 Results

5.5.1 The world with knowledge diffusion

Table 5.5 shows the effects of knowledge diffusion on welfare change across regions compared to the baseline without knowledge diffusion. Apparently, CHN, USA and $RA1$ rise in welfare. However, it is also interesting that not all regions enjoy the positive externality of knowledge spillover. Both India and Russia result in a decline in welfare level.

Table 5.5: Effects of knowledge diffusion on welfare change

	CHN	IND	USA	RUS	EUR	RA1	ROW
Welfare change	+	-	+	-	+	+	+

It is clear that with knowledge spillover, each region will accumulate more knowledge than before. With the increased knowledge stock, firms are able to do more innovation and raise the productivity of technologies, leading to a reduction in the production costs

and, therefore, higher output. This explains why regions benefit from knowledge diffusion. However, what happens to the other regions which suffer from welfare losses? There are several explanations for this. First of all, introducing spillovers to each of the regions implicitly increases the return to capital investment. As more knowledge flows into the home region from abroad, the external knowledge is able to generate new ideas and blueprints when colliding with internal knowledge. The average cost for new knowledge declines, and the return to capital increases since more varieties are produced. The more knowledge flows in, the greater varieties the industry can enjoy, and thus the higher return to capital investment, finally more and more research investment takes places. As from statistics, developed economies have relatively high degree of knowledge spillover, and most of the research and innovation are conducted in these regions. Our results reflect this observation as innovative regions not only benefit from external knowledge diffusion, but also attract new capital investment for further self-innovation, demonstrated by increased inter-temporal knowledge spillover.

Secondly, the knowledge production function exhibits a decreasing returns to scale. It can be seen that the sum of the three elasticities of accessible knowledge ($\alpha_{sa} + \alpha_{sb} + \alpha_{sc}$) is smaller than unity. The growth rate for the investment in innovation declines over time. Moreover, self-innovation requires resources from other sectors, which will decline the consumption level of representative households. These resources invest for R&D to increase the productivity of individual firms, and finally will raise the output for supplying more consumption goods. If the resources devoted for innovation can not reward consumers with higher level of consumption, households will consume the resources directly instead of investing for innovation. Additionally, Spence (1984) discovers that spillovers reduce the incentives for cost reduction. This results in an even larger technological gap between home country and foreign countries who conduct research continuously. This enhances further the shifting of capital investment to developed regions.

Thirdly, we see that the economy-wide productivity increases when activating knowledge spillovers in our model. Sectoral linkage will spread the positive externality in one sector to other sectors. This aggregate positive externality promotes the competitive advantage by increasing the productivity through a scaling effect. A region with higher level of spillovers can gain more than the others.

Finally, the knowledge diffusion affects the regional competition in the world market. An economy is likely to enjoy a high degree of spillover if it is well integrated into the world market. Regions with higher degree of spillovers are more competitive than regions with low degree of spillovers. Hence, regions such as EUR, USA, CHN gain more market share; while region IND and RUS shrink in terms of market share and less goods are exported. With reduced demand for export, firms cut their production and raise the price. In the end, consumers are worse off with lower level of consumption.

5.5.2   The impact of regional unilateral climate policy

We now investigate how the regional unilateral climate policy impacts the economic growth in a world with knowledge diffusion. Europe is recognized as one of the leading players in the battle to mitigate climate change. One of the achievements is the Kyoto Protocol which has significantly reduced the greenhouse gases emissions in Europe. As the first commitment period ended in 2012, these developed economies start to reconsider the future policies for the emission reduction. In the meantime, developing countries are more and more aware of the negative effects of emissions and climate change, and start to take actions to reduce emissions.

To study the effects of regional unilateral climate policy on knowledge and growth, we construct several scenarios for this section. First, we assume that region EUR implements a policy to reduce emission by 20% in 2050 from the 2010 level. We choose EUR as a representative developed economy with strong willingness of cutting emissions and with high level of knowledge spillover intensity. Table 5.6 shows that in such a scenario the welfare level of EUR is significantly reduced.

Table 5.6: The effects of regional climate policies on welfare compared to the case without climate policy in a knowledge diffusion world

Policy region	CHN	IND	USA	RUS	EUR	RA1	ROW
EUR	-	+	+	+	-	+	+
CHN	+	-	-	+	+	-	-
EUR & CHN	+	+	-	+	-	-	-
EUR, CHN & USA	+	+	-	+	-	-	-

It is interesting to see that all the other regions in the world have positive effects on their welfare level expect China. This suggests that the negative impacts of climate policy on welfare in Europe is passed into China through international trade.

We then study how the regional welfare changes if only China adopts an emission reduction policy. The results are shown in the second row of Table 5.6. It is clear that climate policy in China will lead to an increase of the prices of exported goods, particularly energy intensive products. Regions importing such goods will suffer from the price increase. We see the decline in welfare for USA, $RA1$, and IND compared to the case without climate policy. Consumers in region RUS and EUR are slightly better off.

It is surprising that China itself is not worse off. This is due to the fact of high energy intensive production in Chinese firms and large supply of coal. When implementing climate policy, the price of energy goes up if firms continue to use energy as the input for production, and thus firms substitute energy with other materials. The domestic demand for energy declines and energy firms will expand its exports by supplying more to foreign market. From the results we see that the export of coal from China increases significantly if China decides to cut emissions. Meanwhile, affected by the increased

energy price, Chinese firms start to do more innovation to improve the productivity as capital is relatively cheaper. Capital intensive or labor intensive sectors present higher growth compared to energy intensive sectors. Sectors such as *ser*, *man*, *agr* also export more as investment for innovation lowers the production cost and hence gives these firms competitive advantage in the world market. Considering China is one the largest players in the world market for exporting goods, it is reasonable to see such indirect positive benefit for the economy under the pressure of climate mitigation. However, we assume that the emission reduction of 20% is a lax target. A more stringent emission cut target may finally lead to a welfare loss for China.

The third scenario is to assume that both China and Europe implement their own policies to reduce emission by 20%. We find a combined effects from scenario one and two. The main results are the same, EUR suffers from a welfare loss; while CHN receives a gain in welfare. For other regions, the results are mixed. As illustrated in Table 5.6, the overall effect is largely determined by the pattern of international trade. As major players for trade with China, USA, $RA1$ and ROW still suffers from a loss in welfare. But the magnitude of such loss is alleviated through the positive effects of EUR policy.

The fourth scenario represents the case in which USA also decides to cut emissions together with EUR and CHN. The results are shown in the last row of Table 5.6. The welfare level for consumers in USA sharply declines. China is worse off as the US now imports less from China, and thus it is less possible for Chinese firms to retain revenues by shifting residual demand from domestic market to foreign market. EUR is now better off. This is because EUR and USA are competitors in many sectors. The policy of USA reduces the competitive advantage of US products and makes the European goods more attractive. With the three major players in the world cutting emissions, we also find that IND and RUS step in and take over parts of the market share from the three players, and result in a large welfare gain.

5.6 Conclusion

In this paper, we construct a multi-region-multi-sector general equilibrium model with knowledge diffusion. In each of the region and sector, the model features increasing returns to scale through the endogenous growth mechanism developed by Romer (1990). Furthermore, knowledge spillover is modeled explicitly by introducing additional channels for knowledge flows. It is crucial to capture knowledge diffusion for a precise estimation of policy impacts on regional growth. This paper enables a detailed study of the impacts of global climate policy on knowledge and growth.

This study has delivered a new understanding on the impacts of knowledge. Knowledge spillover has impact on regional welfare and growth. However, depending on the status-quo of regional technological level and absorption capacity, the effects of knowledge

diffusion across regions are different. Regions such Europe and the US gain from knowledge diffusion because they are on the frontier of the world technology ladder. New knowledge is easy to be understood when standing on the shoulder of a giant. China benefits as well because its ability to learn through world trade, and the attractiveness of its economy to new capital investment. India and Russia have welfare losses in the knowledge world since they are less integrated into the world knowledge pool, reflected by low spillover intensity coefficients.

By understanding the growth mechanism in a knowledge world, this paper elaborates the impact of climate policy on regional welfare and growth. In general, the regions that implement climate policy will be affected negatively through increased energy price. The negative effects of climate mitigation will be passed onto other regions through international trade. The climate policy leads to a new wave of global production specialization and agglomeration. However, the negative effects may be canceled out if the foreign region is the major competitor with the home country in the world market.

This paper can be further extended and refined in several aspects. It will be interesting to model spillover in a more dynamic way. So far the spillover patterns are fixed in a sense. As the development of the regional economy, regions will change their position in the technology ladder affecting the multilateral spillovers. To investigate and estimate the change in knowledge diffusion effects quantitatively, we first have to obtain a better estimation of the patterns of knowledge development by sectors and by regions. Another issue is how the spillover can be more precisely proxied. There is no direct statistic on spillovers. Data missing in regions and differentiated definition and accounting methods on these count data will largely affect the estimation results. Future work can also be directed to the identification of possible economic trade-offs with regard to climate policies and knowledge spillovers. For example, it has been shown that "clean technologies" provide higher spillovers (Dezchelepretre, 2014), which may indicate a "double dividend" when supporting the green technology sector.

6 Measurement of the "underlying energy efficiency" in Chinese provinces [1]

6.1 Introduction

Emerging economies such as certain Asian and Latin American countries are characterized by relatively high growth rates of energy consumption. The rapid increase of energy consumption in these countries featured by fossil-fuel-based energy system determines local and global environmental problems as well security of supply issues. China, one of the largest energy consumers and emitter of CO2 globally, is also facing these problems. In fact, China's average growth rate of energy consumption is approximately 6% per year and it consumed 21% of the world energy in 2012 (EIA 2013). As the most remarkable growing economy in both energy consumption and GDP, China's energy strategy can significantly affect international discussions on climate change.

In order to promote a reduction of CO2 emissions, a reduction of the local pollution and to promote a higher level of security of supply, the Chinese government has decided to introduce several energy policy instruments. Some of these instruments are market oriented. However, others are non-market oriented instruments such as limits, targets and standard. For instance, in 2007 China revised its energy conservation law and emphasized the relevance of the level of energy efficiency in all sectors of the economy. Further, recently the Chinese government introduced the 12th Five Year Plan that clearly states some binding targets at the end of 2015: a reduction of energy consumption per unit of GDP by 16 percent and a decline of CO2 emissions per unit of GDP by 17%, relative to 2005 levels. Therefore, the Chinese provinces received individual targets for reduction of the level of energy intensity.[2]

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[1]This chapter represents the joint work with Massimo Filippini. A previous version of this paper has been included in the working paper series of CER-ETH. This paper has been presented at Harvard University (Harvard China Project) and MIT (MIT/Tsinghua China Energy and Climate Project). We are grateful to participants for their comments and suggestions.

[2]In the period 1980-2000 China's energy intensity declined 4.52% annually. Though experienced a

With the introduction of these targets, the Chinese government would like to promote an increase in the level of efficiency in the use of energy as well a higher degree of security of supply. However, as discussed in a report by IEA (2009) and by Filippini and Hunt (2011), energy intensity is not an accurate proxy for energy efficiency. This is because changes in energy intensity are a function of changes in several socioeconomic and climate factors. Therefore, for the definition of these policy targets, a better understanding and measurement of the level of energy efficiency of these provinces could improve the effectiveness of interventions done by the central government.

The goal of this paper is to perform an empirical analysis on the measurement of the "underlying energy efficiency" of Chinese provinces using an approach proposed by Filippini and Hunt (2011). This approach is based on the stochastic frontier analysis developed in applied production theory and regards energy as an input into a production function to generate an energy service (such as heating and transport).

Some studies have been published on the measurement of the energy efficiency of the Chinese provinces. All these studies use a Data Envelopment Approach (DEA) and not, as in this study, a stochastic frontier approach. Hu and Wang (2006) estimated the level of energy efficiency using a DEA model and employing provincial data in the periods of 1995-2002. They found a U-shape relation between energy efficiency and per capita income. Moreover, the study confirmed the impact of economic growth on improvement of energy efficiency.[3] Wei et al. (2009) used a DEA approach and panel data to estimate the level of energy efficiency of Chinese provinces. Using a two-step approach the authors of this study tried to identify the drivers of energy efficiency. The results suggest presence of inefficiency in the use of energy and the presence of spatial differences in energy efficiency.

These differences are mainly due to the economic structure, energy structure, the type of government intervention, and the level of technology. Hu and Wang (2010) proposed the estimation of a total-factor energy productivity change index using a DEA approach. The analysis is based on provincial data for the period 2000-2004. In a second part of the analysis, Hu and Wang (2010) proposed to decompose the energy productivity index into "energy efficiency" and "shift in energy use technology".

There are also studies looking into subsectors of the Chinese economy. For example, Xia

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slight increase between 2002 and 2005, it continued with a staggering decline of 18% between 2005 and 2010.

[3] Many papers have also examined the driving forces for energy intensity decline in China using Divisia decomposition method. For instance, Fisher-Vanden et al. (2004) applied the approach using panel data for 2500 industrial enterprises and identified several forces such as research and development expenditures, changes in China's industrial structure as the principal drivers. Hang and Tu (2007) followed similar approach and showed the asymmetric impacts of energy prices on energy intensity. There are also studies in literature on the structural change effects (Liao et al. 2007; Ma and Stern 2008). Song and Zheng (2012) combined decomposition analysis with econometric model and found the significant impacts of rising income as well as limited effect of energy price on the reduction of energy intensity.

et al. (2011) and Zhao et al. (2014) study efficiency issues in the Chinese industry sector while Bi et al. (2014) focus on the power generation sector. Furthermore, Chen and Chen (2010, 2011, and 2013) and Chen et al. (2010) introduce an input-output modeling approach for the analysis of energy consumption and emissions in China.

In this paper, as discussed above, we want to use an alternative approach to measure the level of "underlying energy efficiency" based on stochastic frontier analysis. The advantage of this approach in the context of measurement of energy efficiency is the possibility to take into account the presence of unobserved heterogeneity, to distinguish persistent (time-invariant) from transient (time-varying) inefficiency and to take into account the statistical noise of approximation errors and random behavior. To note, that the estimation and interpretation of persistent and transient inefficiency as complementary parts of the level of productive efficiency is recent.[4]

The paper is organized as follows. Section 2 introduces the specification of aggregate energy demand model and summarizes data. In Section 3, econometric specifications have been explained. Section 4 presents and discusses estimation results. Section 5 summarizes the estimated "underlying energy efficiency". Section 6 concludes the paper.

6.2 Model specification and data

The analysis of the level of "underlying energy efficiency" of the Chinese provinces is based on the econometric estimation of following aggregate energy demand frontier function:

$$E_{it} = E(P_{it}, Y_{it}, HS_{it}, HD_{it}, POP_{it}, ISH_{it}, SSH_{it}, HCDD_{it}, BUS_{it}, CAR_{it}, UEDT_t, EF_{it}),$$
$$(6.1)$$

where E_{it} is the aggregate energy consumption for province i over time t in million tonnes of coal equivalent (Mtce); Y_{it} is the real GDP in billion 1996 Chinese Yuan (CNY); P_{it} is the real energy price index (2003=100); HS_{it} indicates the average household size computed as the ratio between population and household units; HD_{it} is the household density calculated as the ratio between number of household and area size; POP_{it} is the population size; $HCDD_{it}$ is the sum of heating and cooling degree days; BUS_{it} and CAR_{it} are the number of buses and cars, representing the energy demand in transport sector; ISH_{it} and SSH_{it} are the share of the industrial sector and the share of the service sector in % of the GDP, respectively; $UEDT_t$ captures some important unmeasured factors that influence all provinces simultaneously, e.g. general technical progress, awareness of

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[4]Generally, the empirical literature on the measurement of productive efficiency interpret time-varying and time-invariant inefficiency indicators as alternative measures of productive efficiency. See for instance Filippini and Hunt (2012). Only recently Kumbhakar et. al. (2012) introduced a new interpretation of these inefficiency measures based on complementarity. In this paper we decided to follow this approach.

emission reduction and climate change. Finally, EF_{it} is the level of "underlying energy efficiency" of each of the Chinese provinces in year t.

Unfortunately, this level is usually not directly observed for an economic system and, therefore, has to be estimated. As previously discussed, in this paper, following the approach suggested by Filippini and Hunt (2011), we estimate the level of "underlying energy efficiency" of Chinese provinces by using a stochastic energy demand frontier function. This frontier represents the minimum level of energy consumption necessary for each province to produce any given level of energy service (Filippini and Hunt 2011, 2013). Therefore, the frontier function defines a boundary, deviations from which can be interpreted as inefficiency in the use of input energy.

Aigner et al. (1977) proposed the stochastic frontier model as an econometric technique to estimate the level of efficiency in use of inputs. In this econometric model, variation of the dependent variable unexplained by independent variables is split in two parts: statistical noise and productive inefficiency.

Following Filippini and Hunt (2011, 2012) and using a log-log functional form the stochastic energy demand frontier function can be specified as follow:

$$e_{it} = \alpha + \alpha^p p_{it} + \alpha^y (y_{it})_{lag} + \alpha^{hd} hd_{it} + \alpha^{hs} hs_{it} + \alpha^{pop} pop_{it} + \alpha^{ISH} ISH_{it} + \alpha^{SSH} SSH_{it}$$
$$+ \alpha^{hcdd} hcdd_{it} + \alpha^{bus} bus_{it} + \alpha^{car} car_{it} + \alpha^t t + \alpha^{t^2} t^2 + u_{it} + v_{it},$$
(6.2)

where e_{it} is the natural logarithm of aggregate energy consumption (E_{it}); p_{it} is the natural logarithm of the real energy price (P_{it}); y_{it} is the natural logarithm of GDP (Y_{it}); hd_{it} is the natural logarithm of the household density (HD_{it}); hs_{it} is the natural logarithm of the household size (HS_{it}); pop_{it} is the natural logarithm of population (pop_{it}); $hcdd_{it}$ is the natural logarithm of the heating and cooling degree days ($HCDD_{it}$); bus_{it} and car_{it} are the natural logarithm of number of buses (BUS_{it}) and cars CAR_{it}, respectively; ISH_{it} and SSH_{it} are as defined above; t and t^2 are used as proxies for $UEDT_t$.[5]

The error terms in equation 6.2 have two parts. The first part, , is the normal noise term assumed to be normally distributed. The second term, contains information on the distance between the frontier and the actual input and is interpreted as an indicator of the inefficiency levels. It is a one-sided non-negative random disturbance term that can vary over time. For this term a distributional assumption has to be made. Generally researchers choose the half-normal distribution. However, other assumptions regarding the distribution of inefficiency term can be made such as exponential, truncated-normal

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[5]As suggested in Filippini and Hunt (2012), time dummies can also be used as an alternative to capture the impacts of UEDT. In a preliminary analysis we also used time dummies and the results were relatively similar.

and gamma distributions.

Summarizing, in equation 6.2 the time trend should capture impact on energy consumption due to technological, organizational, and social innovation, whereas should capture improvements in the level of efficiency in use of energy. As discussed in more details in Filippini and Hunt (2013), in a more general interpretation the time trend should capture shifts in isoquants, whereas should capture the distance from the isoquant.

Based on the values of u_{it} and following Jondrow et al. (1982) it is possible to estimate the level of "underlying energy efficiency" of a province using the conditional mean of the efficiency term $e[u_{it}|u_{it} + v_{it}]$. The level of "underlying energy efficiency" can be expressed in the following way:

$$EF_{it} = \frac{E_{it}^F}{E_{it}} = \exp(-\hat{u}_{it}), \tag{6.3}$$

where E_{it} is the observed energy consumption and E_{it}^F is the frontier or minimum demand of the ith state in time t. A value EF_{it} of one indicate a province on the frontier (100% efficient), while non-frontier provinces are characterized by a level of EF_{it} lower than 100%.

This study is based on a balanced China panel data set for a sample of 29 provinces observed over the period 2003 to 2012 (2003-2012). This paper is restricted to study provinces, autonomous regions, and municipalities in mainland China. Due to incomplete information in statistics, Tibet and Hainan are excluded from this study. For simplicity, thereafter all the units of observations are called provinces. The data set is based on information taken from China National Bureau of Statistics reports "China Statistical Yearbook" (1997-2009)[6] and "China Urban Life and Price Yearbook" (2009). Table 6.1 presents the descriptive statistics of key variables.

6.3 Econometric specifications

The estimation of a stochastic frontier function with panel data can be performed using a number of different SFA model specifications such as the pooled model (PM hereafter), the random effects model (REM hereafter), the true fixed effects model (TFEM hereafter), and the true random effects model (TREM hereafter).[7] Moreover, in some recent studies on the aggregate energy demand by Filippini and Hunt (2012, 2013), part of these stochastic frontier models, have been estimated using an adjustment introduced by Mundlak (1978). This adjustment takes into account a potential unobserved heterogeneity bias and separates transient inefficiency from time invariant unobserved heterogeneity.

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[6]The yearbooks of China always have one-year delay, which means yearbook in 1997 reports the statistics of 1996.

[7]For a general presentation of these models, see Greene (2008) and Farsi and Filippini (2009).

Table 6.1: Descriptive statistics of explanatory variables

	Description	mean	sd	min	max
E	Energy consumption (Mtce)	111.59	72.34	10.66	388.99
P	Real price index (2003=100)	155.40	35.65	100	251.83
Y	Real GDP (billion 2003CNY)	859.97	743.62	38.53	3,814
POP	Population (10000 persons)	4,484	2,592	534	10,594
HD	Average household density (household per km^2)	143.41	224.49	1.89	1590.56
HS	Average household size (persons)	3.19	0.31	2.41	4.40
ISH	Share of industrial sector in % of GDP	41.87	6.92	18.42	56.51
SSH	Share of service sector in % of GDP	39.30	7.75	28.60	76.50
HCDD	Heating and cooling degree days	658.44	628.29	0	2585.6
BUS	Number of buses	11,958	8,354	1,011	53,089
CAR	Number of cars (10000)	186.89	181.13	4.10	1037.42

As discussed in details in Farsi and Filippini (2009) and Filippini and Hunt (2013), all these models have their relative advantages and disadvantages and the choice of model is not straightforward. It depends upon the goal of the exercise and type of data and variables that are available. Generally, one of the most important issues to consider in estimating energy demand frontier function using aggregate data is to use an econometric specification that takes into account of the presence of time-invariant unobserved heterogeneity variables, time invariant or persistent inefficiency and transient inefficiency. In our case, due to the relatively large size and heterogeneity in the morphology and socioeconomic organization of Chinese provinces, we can expect to observe transient and persistent inefficiency in the use of energy as well a model specification that could suffer from unobserved heterogeneity bias.

Unfortunately, there is no relatively straightforward econometric model that can be estimated in order to simultaneously obtain information on persistent and transient inefficiency while controlling for unobserved heterogeneity bias. For instance, Kumbhakar et al. (2014), Tsionas and Kumbhakar (2014) and Colombi et al. (2014) have proposed some relatively complex econometric approaches that provide separate estimates of these two components of efficiency. Recently, Filippini and Greene (2014) have proposed a relatively straightforward estimation method where the extreme complexity of the log likelihood is reduced by using simulation and exploiting the Butler and Moffitt (1982) formulation. However, this approach is still being tested.

In our empirical analysis we decided to follow another approach to measure persistent and time-varying inefficiency based on the estimation of several independent models. For this reason, we estimate the basic version of the REM proposed by Pitt and Lee (1981), a Mundlak version of this model, the TREM proposed by Greene (2005a, 2005b) and a Mundlak version of the TREM.[8] The first two models provide information on the

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[8]Another alternative approach to measure the transient part of efficiency is the True Fixed Effects

level of persistent inefficiency, whereas the last two models give information on transient inefficiency. Of course, we are aware that this approach based on the estimation of separate models is not completely satisfactory.

In the basic form of REM proposed by Pitt and Lee (1981), individual random effects are considered inefficiency indicators rather than time-invariant unobserved heterogeneity as in the traditional literature on panel data econometric methods. In this model, the individual effects u_i are assumed to be half-normal distributed and to be uncorrelated with the explanatory variables. As long as this assumption holds, the estimators are not affected by a heterogeneity bias. As discussed by Filippini and Hunt (2012), one problem with the REM is that any time-invariant, province-specific heterogeneity is included in the inefficiency term. Further, the level of inefficiency does not vary over time. Therefore, the REM tends to provide information on the level of persistent inefficiency.

The TREM is obtained by adding to the PM proposed by Aigner et al. (1977) an individual random effect that should capture the time-invariant unobserved variables. The TREM estimates unit-specific constants that are designed to capture unobserved heterogeneity by simulated maximum likelihood, so that the remaining elements in the error term, including inefficiency, vary freely over time.[9] This model has the advantage to be able to differentiate time invariant unobserved heterogeneity from the time varying part of efficiency. This is a clear advantage of the TREM with respect to the basic version of the PM. However, this model tends to underestimate the level of inefficiency because the persistent part of inefficiency is captured by individual random effects. In situations characterized by the presence of persistent inefficiency in the use of resources, the TREM estimates just one part of the level of inefficiency. Therefore, the values of inefficiency in use of energy obtained using TREM tend to represent the transient part of inefficiency.

As discussed by Farsi et al. (2005a, 2005b), both approaches mentioned above (REM and TREM) can suffer from the "unobserved variables bias". To address this issue, Farsi et al. (2005a, 2005b) proposed to use the Mundlak adjustment in the estimation of model 6.2.

In the Mundlak version of REM (hereafter MREM) the correlated components of unobserved heterogeneity are absorbed by the group-means of explanatory variables, whereas uncorrelated components are stuck in individual effects. The additional assumption that underlies in this model is that only uncorrelated, i.e. separable components of unobserved heterogeneity are in the individual effects, which as explained above, in this model are interpreted as inefficiency terms. The correlated, i.e. non-separable components of unobserved heterogeneity are considered in the coefficients of auxiliary equation and thus not interpreted as inefficiency. We believe that the MREM is an appealing model because it is relatively intuitive, easy to estimate, avoids the unobserved heterogeneity bias and separates the individual effects in two parts - the persistent inefficiency term

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model Greene (2005a, 2005b).

[9]The TREM is estimated using a simulated maximum likelihood procedure.

and the non-separable time-invariant unobserved variables.

Another issue related to the estimation of an aggregate energy demand function is the potential endogeneity problem of the GDP variable, especially in models that try to explain energy consumption in developing or emerging countries.[10] As recently discussed by Greene (2011) and Mutter et al. (2013), it is difficult to account for endogeneity in SFA models, particularly because of the non-linearity of econometric specification. In fact, no accepted approach exists for SFA models. This is the reason why most of the empirical studies using SFA do not consider this potential econometric problem. Recently, Mutter et al. (2013) investigated the impact of endogeneity on inefficiency estimates using the SFA approach. The results show that the degree of severity of problem depends across model specifications and type of data. As a robustness check, we decided to investigate the endogeneity issue of GDP using residual inclusion approach (2SRI hereafter) for non-linear models suggested by Terza et al. (2008). This approach, although econometrically not completely satisfactory, tries to solve the endogeneity problem by using a two-stage method. In the first stage, the endogenous variable is regressed against instrumental as well as exogenous variables. In the second stage, the original equation is estimated by including the residuals obtained in the first stage.

The values of the coefficients and the values of the level of energy efficiency obtained using this approach are highly similar to the one obtained with the Mundlak versions of the REM and TREM that do not consider possible endogeneity of the GDP variable.[11]

Given the discussion above, four models are estimated in this paper: Model I is the REM; Model II is the Mundlak version of the REM (hereafter MREM); Model II is the TREM; Model IV is the Mundlak version of the TREM (hereafter MTREM). As previously discussed, the Mundlak versions of REM and TREM are considered the most interesting models for the estimation of persistent and transient level of efficiency in the use of energy, respectively. Table 6.2 summarizes the four models.

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[10]To note that in the literature using data for industrialized countries characterized by a relatively small weight of energy to GDP, this potential endogeneity problem is rarely considered.

[11]The instruments considered in our empirical analysis are the ratio of engineers in professional personnel (ENG_{it}), the number of secondary schools (SCH_{it}) and the number of teachers (TEA_{it}). In order to verify the validity of the instruments, we estimate a regular fixed effects model. To test for weak instruments we compute the Cragg-Donald Wald F test statistic. The value of this statistic (12.21) is larger than the critical value at 10% level of significance (9.08) suggested by Stock-Yogo (2003). Therefore, we reject the hypothesis that instruments are weak. The Hansen J statistic for testing the overidentification of all instruments does not reject the null hypothesis of valid instruments (Chi-sq(2)=0.50, P-Value=0.78). All these results show that we were able to find reasonable instruments. The estimation results are reported in the appendix

Table 6.2: Econometric specifications of the stochastic cost frontier

	Model I REM	Model II MREM	Model III TREM	Model IV MTREM
State effects	-	$\alpha_i = \gamma \bar{X}_i + \delta_i$ $\bar{X}_i = \frac{1}{T}\sum_{t=1}^{T} X_{it}$ iid(0,σ_δ^2)	-	$\alpha_i = \gamma \bar{X}_i + \delta_i$ $\bar{X}_i = \frac{1}{T}\sum_{t=1}^{T} X_{it}$ iid(0,σ_δ^2)
Random error ε_{it}	$\varepsilon_{it} = \alpha_i + v_{it}$ $\alpha_i \sim N^+(0,\sigma_\alpha^2)$ $v_{it} \sim N^+(0,\sigma_v^2)$	$\varepsilon_{it} = \delta_{it} + v_{it}$ $\delta_{it} \sim N^+(0,\sigma_\delta^2)$ $v_{it} \sim N^+(0,\sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0,\sigma_u^2)$ $v_{it} \sim N^+(0,\sigma_v^2)$	$\varepsilon_{it} = u_{it} + v_{it}$ $u_{it} \sim N^+(0,\sigma_u^2)$ $v_{it} \sim N^+(0,\sigma_v^2)$
Inefficiency	$E(\alpha_i\|v_{it})$	$E(\delta_i\|v_{it})$	$E(u_{it}\|v_{it})$	$E(u_{it}\|v_{it})$

6.4 Estimation results

The estimation results of frontier energy demand models using the four models are given in Table 6.3. Several of the estimated coefficients and lambda[12] have the expected signs and are statistically significant at the 10% level. Generally, the value of coefficients of REM and TREM are similar but to some extent different from the values of the coefficients of the Mundlak version of these two models that take into account the problem of unobserved heterogeneity bias. For instance, the values of income elasticity obtained in REM and TREM are much lower than the ones obtained in all other models.[13] The results obtained with MREM and MTREM models are relatively similar. This similarity in the results confirms that Mundlak adjustment method applied to REM and TREM models can be a valid approach in stochastic frontier analysis. Therefore, MREM and MTREM models should be preferred to REM and TREM models.

The estimation results indicate that price does not influence energy demand. This result may be due to the fact that in China energy prices are relatively low and fully controlled by the government. Therefore, the variation across provinces of the price is relatively low.

The income elasticity (α^y) is around 0.76 and statistically significant in all two models with the Mundlak corrections (MREM, MTREM). This implies that a 1% increase in GDP will lead to a 0.76% increase in energy demand. Therefore, as expected for emerging countries, the income elasticity of energy demand is relatively high. In fact, the estimated coefficient is very close to the elasticity reported in statistics. According to the National Bureau of Statistics of China (NBS 2013), the average elasticity of energy demand with respect to income during the period 2003-2012 is approximately 0.84.

The coefficients of the three variables, household size, household density, and population, represent the impact of demographic variables on aggregate energy demand. As expected, in all econometric models the coefficient of population is positive and significant, whereas

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[12]Lambda (λ) gives information on the relative contribution of uit and vit on the decomposed error term ε_{it} and shows that in this case, the one-sided error component is relatively large.

[13]Given the fact that we are using a log-log functional form, the estimated coefficients can be interpreted as elasticities.

Table 6.3: Estimation results

Variable	Model I REM	Model II MREM	Model III TREM	Model IV MTREM
P	-0.000	-0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Y	0.585***	0.759***	0.612	0.765***
	(0.062)	(0.098)	(0.022)	(0.107)
HS	-0.430***	-0.403***	-0.366***	-0.425***
	(0.128)	(0.103)	(0.046)	(0.046)
HD	-0.179***	-0.117***	-0.135***	-0.148***
	(0.073)	(0.018)	(0.005)	(0.006)
POP	0.175*	0.249***	0.069***	0.301***
	(0.094)	(0.061)	(0.018)	(0.018)
HCDD	-0.005	-0.002	-0.002	-0.003
	(0.006)	(0.006)	(0.002)	(0.003)
BUS	0.102***	0.097***	0.084***	0.093***
	(0.031)	(0.031)	(0.013)	(0.031)
CAR	0.070***	0.072***	0.071***	0.079***
	(0.020)	(0.020)	(0.012)	(0.019)
SSH	-0.005*	-0.006**	-0.005***	-0.005***
	(0.003)	(0.003)	(0.001)	(0.001)
ISH	0.003	0.002	0.002*	0.003*
	(0.002)	(0.002)	(0.001)	(0.001)
T	0.017	-0.004	0.019**	-0.005
	(0.011)	(0.015)	(0.001)	(0.020)
T2	-0.002***	-0.002***	-0.003***	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)
M(P)		0.007**		0.014***
		(0.003)		(0.001)
M(Y)		-0.750***		-0.769***
		(0.127)		(0.109)
M(BUS)		0.190*		0.041***
		(0.114)		(0.038)
M(CAR)		0.293***		0.360***
		(0.093)		(0.024)
M(ISH)		0.012***		0.013***
		(0.003)		(0.001)
Constant	-1.552	5.432***	-0.181	4.340***
	(2.258)	(1.239)	(0.276)	(0.310)
Log likelihood	354.7	371.0	355.3	365.6
Lambda	8.943***	5.477***	1.059***	0.898***

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

the coefficient of household size is negative and significant. Thus, ceteris paribus, an increase of the household size implies a decrease of energy consumption. This result may be due to the presence of economies of scale in the production of some residential energy services. For instance, the size of a refrigerator is unlikely to vary proportionally with the number of household members. In order to reduce the growth rate of energy demand, the government could introduce policy instruments to encourage families to live together. The traditional Chinese philosophy of life supports this behavior. Similarly, an increase in the household density also seems to contribute to the decline in energy demand. This means that urbanization may reduce energy consumption through economies of scale in the production of some residential energy services such as heating and cooling services. For instance, multifamily houses tend to consume less energy per square meters than single family houses.

The estimated coefficients of HCDD is small and insignificant in all models. A possible explanation for this result is the relatively low penetration rates of heating systems in some provinces. In reality, only northern and a small part of central region in China are heated legally according to the construction code of China. On the other side, energy consumption for cooling contributes to a small part of total energy consumption in residential and service sector (Zhang 2013).

As expected, the signs of the estimated coefficients of bus and car are positive. Both coefficients are statistically significant. This implies that the transport sector is one of the driving forces of the energy demand growth in China. The positive sign of the estimated coefficient of the share of industrial sector to GDP as well the estimated coefficient of the share of service sector to GDP have the expected signs and are significant. However, the value of these coefficients is relatively small. The UEDT is captured by the coefficients of t and t^2 combined. The value of these coefficients is also relatively small. As discussed by Kumbhakar and Lowell (2000), it is not easy to separate the effects of technical change from the effects of productive efficiency in the estimation of stochastic frontier models. Finally, the majority of the Mundlak terms are significant. To note, in order to keep the number of variables relatively small and to avoid multicollinearity problem, only a part of the explanatory variables has been introduced as Mundlak's adjustment.[14]

6.5 Energy efficiency

Table 6.4 gives a summary of the energy efficiency scores estimated with all four models. As expected, the scores obtained with REM and MREM are lower than the scores obtained with TREM and MTREM. Further, the values of energy efficiency obtained using MREM (0.81) are higher than the values obtained with the basic REM (0.71).

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[14]In order to select the variables to consider in the Mundlak adjustment, we estimate a regular fixed and random effects model and we used an Hausman test. The model specification used in the estimation of the Mundlak version of REM and TREM was confirmed by the results of the Hausman test.

Table 6.4: Energy efficiency scores of different estimations

Model	OBS	MEAN	S.D.	MIN	MAX
REM	290	0.7122	0.1592	0.3686	0.9824
MREM	290	0.8078	0.1433	0.5581	0.9794
TREM	290	0.9627	0.0154	0.8588	0.9899
MTREM	290	0.9670	0.0120	0.8832	0.9903

Table 6.5: Pair-wise Spearman's rank correlation coefficient between different model estimations

	REM	MREM	TREM	MTREM
REM	1.0000			
MREM	0.7690	1.0000		
TREM	0.2182	0.2872	1.0000	
MTREM	0.1340	0.3350	0.8286	1.0000

As discussed above, the reason for this difference is due to the ability of MREM to distinguish persistent inefficiency from time-invariant unobserved variables. Finally, the values of energy efficiency calculated with MTREM are relatively high (0.97). In this study, as argued before, we propose to interpret the values obtained with MREM as the persistent component of level of energy efficiency and the values from MTREM as the transient component.

In Table 6.5 we report the values of Spearman's rank correlation coefficient of the energy efficiency values obtained with all models that consider the Mundlak adjustment. To note, that the rank correlation coefficient between the level of efficiency obtained using REM and MREM is 0.77. Also, the rank correlation coefficient between the level of efficiency obtained using TREM and MTREM is high (0.83). Further, the correlation coefficients between MTREM model and MREM model are relatively low (0.34). This result indicates that persistent "underlying energy efficiency" and transient "underlying energy efficiency" are not highly correlated. Finally, the Spearman's rank correlation coefficient between the estimated "underlying persistent energy efficiency" from the two models MREM and "energy intensity" is -0.48, whereas the Spearman's rank correlation coefficient between the estimated "underlying transient energy efficiency" from MTREM and energy intensity is -0.26 (see Table 6.6). This result confirms that energy intensity should not be used as a proxy for energy efficiency.

The values of level of energy efficiency can be used to identify three groups of provinces namely, relatively efficient provinces (average value of the level of efficiency higher than

Table 6.6: Pair-wise Spearman's rank correlation coefficient between efficiency scores from all models and energy intensity (EI)

	REM	MREM	TREM	MTREM
EI	-0.4892	-0.4798	-0.4749	-0.2552

the third quartile of the distribution of efficiency), relatively inefficient states (average value of the level of efficiency lower than the median value) and moderately efficient states (average value of the level of efficiency between the median and the third quartile value).

In Table 6.7, we report the classification of provinces based on average value of the energy efficiency obtained during the period 1996-2008 and using the results of MREM and MTREM models. From this table it is interesting to observe that: a) there is no clear relationship between the efficiency level and the degree of economic development. For instance, well developed provinces such as Zhejiang, Jiangsu, Fujian, Beijing, Shanghai, Guangdong belong to different efficiency groups; b) some of the provinces show a relatively high level of persistent efficiency but a relatively low level of time varying efficiency, whereas some of the provinces show a relatively low level of persistent efficiency but a relatively high level of transient efficiency; c) it is possible to identify some spatial clusters in the level of energy efficiency.

The maps in figures 6.1 and 6.2 illustrate the average level of energy efficiency of all provinces observed during the period of the analysis from model MREM and MTREM. The greener the color is, the more efficient a province is. Both figures show that there are significant differences between provinces in term of persistent as well transient level of energy efficiency.

Figure 6.1: Geographic illustration of the level of persistent energy efficiency across provinces (MREM model)

Table 6.7: Classification of provinces based on the estimated average energy efficiency over the period 1996-2008

	MREM	MTREM
Beijing	***	*
Tianjin	***	***
Hebei	*	*
Shanxi	*	*
Inner Mongolia	*	*
Liaoning	*	**
Jilin	*	*
Heilongjiang	***	***
Shanghai	*	*
Jiangsu	*	*
Zhejiang	**	***
Anhui	***	**
Fujian	***	*
Jiangxi	**	*
Shandong	*	**
Henan	**	***
Hubei	*	**
Hunan	*	*
Guangdong	**	***
Guangxi	**	***
Chongqing	*	*
Sichuan	*	***
Guizhou	*	*
Yunnan	***	**
Shaanxi	***	***
Gansu	*	**
Qinghai	**	*
Ningxia	*	**
Xinjiang	***	*
Mean	0.8078	0.9670
Median	0.8343	0.9677
75% precentile	0.9570	0.9684

NB: The classification in the table are based on the following rules:

- **Inefficient province**: Marked with "*", where a province's average value of estimated "underlying energy efficiency" is lower than the median estimated "underlying energy efficiency".

- **Moderately efficient province**: Marked with "**", where a province's average "underlying energy efficiency" is between the median and the 75% quartile estimated "underlying energy efficiency".

- **Efficient province**: Marked with "***", where a province's average "underlying energy efficiency" is higher than the 75% quartile estimated "underlying energy efficiency".

Figure 6.2: Geographic illustration of the level of transient energy efficiency across provinces (average value, MTREM model)

6.6 Concluding remarks

In this study, we have estimated the level of "underlying energy efficiency" for Chinese provinces. For this purpose, a log-log aggregate energy demand frontier model was estimated employing data of 29 provinces observed between the periods from 2003 to 2012. The frontier model approach used in this study is based on Filippini and Hunt (2011, 2012).

From the econometric point of view, several estimators are possible for panel data frontier models. In the choice of econometric techniques, special attention has been given to the presence of unobserved heterogeneity variables and to the fact that some models provide information on the level of *persistent* "underlying energy efficiency" and some others provide information on the level of *transient* "underlying energy efficiency". In this study, in addition to the widely used REM and TREM, we estimate these models using the Mundlak adjustment (1978).

Our analysis shows that energy intensity cannot measure accurately the level of efficiency in the use of energy in Chinese provinces. Further, our empirical analysis shows that the average value of the *persistent* "underlying energy efficiency" is around 0.81 whereas the average value of the *transient* "underlying energy efficiency" is approximately 0.97. Finally, the results indicate that exogenous factors such as technical change play an important role in decreasing the consumption of energy.

From an energy policy point of view the empirical analysis reported in this paper shows that energy consumption targets, as the ones introduced recently by the Chinese government, should also be defined by considering the level of "underlying energy efficiency" of single provinces and not only the energy intensity. The energy policy instruments should give on one side incentives to the provinces to be on the frontier. On the other side, the energy policy instruments should be more incentive to adopt new and more efficient technologies.

7 Convergence of operational efficiency in China's provincial power sectors [1]

7.1 Introduction

China's electricity generation market experienced unprecedented expansion in the past decade as the country worked to ensure sufficient and secure levels of electricity supply for sustained and high-speed economic growth. From 1996 to 2008, the annual average growth rate of power capacity was approximately 12.5%, boosted by the acceleration of industrialization and urbanization. China now owns 960 GW of installed generation capacity, second only to the United States' 1075 GW. Yet, electricity generation mainly occurs in coal-fired power plants. For the improvement of efficiency and reduction of emissions, the power sector faces a series of market reforms from the 1980s initiated by the government. Even though some reforms have taken place in the power sector, relative monopoly is still surviving and hampering the development of the liberalized economy (Wang and Chen 2012), indicating lower effectiveness of the reforms in improving the efficiency and productivity from the perspective of market structure.

The government also provides a number of technological initiatives to promote energy efficiency and pollution abatement. These measures mainly focus on the closure of older, less efficient plants and the construction of new plants with advanced technologies, for instance supercritical and ultra-supercritical coal plants. As summarized in Zhou et al. (2010), massive attention is devoted to energy efficiency measures with focus on the so-called "top ten priorities" and "Ten key Projects". The largest energy-consuming power plants signed agreements to improve their energy performance through the "Top 1000 Program" (IEA 2010c). Several targets have also been announced officially for the increase of generation capacity and the promotion of renewable energy.[2] However, the rapidly

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[1]This chapter represents the joint work with Vishal Jaunky. The paper has been accepted for publication in *The Energy Journal*.

[2]To reach the target for installed capacity in 2020, 70GW of nuclear, 100GW of wind, 1.8GW of solar are needed according to IEA (2010c). A new Renewable Energy Law and many regulations are designed

expanding generating capacity in China cannot meet the even faster growth of electricity demand.[3] Lack of unified national grid system and limited access to the most advanced technologies cause the generating and transmission systems to remain underdeveloped and inefficient in spite of substantial investment. An even more challenging target has been set in the 12th Five-Year-Plan, which clearly mentions the reduction of energy consumption per Yuan 10,000 of GDP by 32% compared to the 2005 level. China also promises to reduce its CO2 emission intensity by 40-45% in 2020 compared to 2005 in the United Nations Framework Convention to Climate Change (UNFCCC).

China's electricity sector is particularly important for achieving these targets, as it accounts for nearly half of greenhouse gas emissions (Steenhof and Fulton, 2007). Around 80% of electricity generation in China comes from coal-fired power plants (NBS, 2013). The energy intensity and CO2 emissions in China is highly dependent on coal consumption. Any inefficient use of coal in electricity generation results in higher coal consumption, which keeps the energy intensity and CO2 emissions at a higher level. Despite the importance of the electricity industry in China, very few studies have investigated the trend in the efficiency of electricity generation at the provincial level. For this purpose, we have to understand the status-quo of the electricity efficiency across Chinese provinces.

In this paper, we first estimate the operational efficiency using DEA method. In the second stage, several convergence models are employed to investigate the change of operational efficiency over time and across provinces.[4] We examine the dynamic changes in operational efficiency from two perspectives: the change in technical efficiency and the change in productivity. There are reasons to study operational efficiency and its change. The level of operational efficiency provides us with information on individual provincial power sectors' performance. As this study distinguishes inefficient and efficient provinces in terms of operational variables, we can identify suitable models for less efficient provinces to emulate. Policies and regulations used in efficient provinces may also be suitable role models for inefficient provinces in order to improve their performance. Moreover, operational efficiency tells us how much more electricity can be produced to fulfill our demand. This is particularly important for the government in terms of energy supply security.

Nevertheless, changes in efficiency can only reflect the development of performance of individual provinces and cannot account for the degree of effectiveness of the energy policies across provinces. With convergence analysis we can explore the cross-province disparities[5] in electricity generation performance and relate it with the effectiveness of the

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to support the development of renewable energy industries.

[3]China has faced a severe electricity crisis since 2000. In 2004, 26 out of 31 provinces experienced electricity shortages. The total shortage was about 35 GW. This gap remained or even increased since then.

[4]The decision-making unit (DMU) in this study is the provinces.

[5]Cross-operational efficiency convergence can crop up from diminishing returns of capital, economies of scale, convergence in the quality of coal, etc.

provincial energy policies. If the electricity efficiency gap among provinces diminishes over time, then the Chinese government may be less concerned about the effectiveness of their regional energy policies especially with regards to the power sector. If, on the other hand, the gap tends to persist over time, then the Chinese government should "introspect" on areas it is lagging behind and enact policies to enhance the efficiency of provincial power sectors. Our results reveal a converging pattern across Chinese provinces. Specifically these provinces are found to converge faster to their own operational efficiency long-run growth paths than to a common one. We also find evidence that reform of pricing system, unity of the grid distribution network, urbanization and economic structural change, avoidance of government intervention, are necessary to increase efficiency.

This paper is organized as follows. Section 2 reviews the convergence literature with special reference to the power sector. Section 3 describes the methodologies. Section 4 summarizes the data. Section 5 presents efficiency models and results. Section 6 shows various convergence models and our main findings. Section 7 provides some policy implementations and concludes the paper.

7.2 Review of literature

The concept of convergence is borrowed from the neoclassical growth literature (Solow, 1956). It essentially prophesies a catching-up of the poor countries with the rich ones in terms of income. Income convergence is achieved if differences in relative income are falling over time. Recently, the convergence concept has also been applied to the field of energy. So far, the literature has focused on carbon dioxide ($CO2$) emissions. Nguyen Van (2005) makes use of principally non-parametric distribution dynamics techniques to study $CO2$ emissions for 100 countries over the period 1966-1996. His results reveal a tendency for $CO2$ emissions in industrialized countries to converge even as he discerns little evidence of convergence for the whole sample. Romero-Avila (2008) uncovers both stochastic and deterministic convergence of $CO2$ emissions, occurring in 23 developed countries over the period 1960-2002. Westerlund and Basher (2008) find indication of stochastic convergence for a group of 28 developed and developing countries over the period 1870-2002. Jobert et al. (2010) report further evidence of absolute convergence in $CO2$ emissions for 22 European countries over the period 1971-2006. Marrero (2010) finds evidence of conditional convergence of greenhouse gases (GHG) emissions for 27 European countries over the period 1990-2006.

From the electricity perspective, the convergence phenomenon has also been investigated. Robinson (2007) tests for β-convergence hypothesis by using annual electricity price data for 9 European Union members over the period 1978-2003. The hypothesis holds for most of the countries in his sample. Using several parametric and non-parametric concepts, Jaunky (2008) uncovers evidence of electric power consumption divergence for 22 African countries for the period 1971-2002. Using non-parametric techniques, Maza

and Villaverde (2008) test the residential per capita electricity consumption convergence for 98 countries over the period 1980-2007 and report weak evidence of such convergence. Zachman (2008) investigates whether a common European market for electricity for 11 European countries over the period 2002-2006 is emerging. He finds evidence of stochastic convergence for some countries only.

Liddle (2009) detects both σ-convergence and γ-convergence in electricity intensity of 22 IEA/OECD countries. He also supplies evidence of commercial electricity intensity convergence toward a bell-shape distribution while industry electricity intensity is converging toward two groups such as one with relatively high electricity intensity and another with relatively low electricity intensity. Jaunky (2010) provides evidence of a divergence pattern for electric power consumption among the Southern African Power Pool (SAPP) members over the period 1995-2005. Jaunky (2013) finds some mixed evidence of neoclassical convergence of TE for the SAPP members over the period April 2003-March 2010. His study especially reveals the occurrence of club-formation and γ-divergence.

Recently, Jiang and Wu (2008) analyze the electricity productivity convergence of 30 Chinese provinces over the period 2000-2006. They define electricity productivity as output divided by final electricity use. They use the panel data model to test the conditional convergence and introduce province-specific factors such as electricity price, investment ratio, FDI, technologies, and international trade. Their panel data estimation results show that the gap between the eastern China and western China is decreasing, but there is no absolute convergence in electricity-productivity levels. Furthermore, the influence of electricity price, investment, FDI, technologies and openness on province-specific electricity-productivity growth rates are found to be limited, though the industrial structure negatively influences the electricity productivity growth. We investigate the provincial differences explicitly instead of the general trends in regional level. To conduct a complete analysis both parametric and non-parametric convergence models are employed for this study.

7.3   Methodology

To analyze the operational efficiency convergence of the Chinese provinces, both technical efficiency and productivity change indices are computed. The electricity efficiency scores across provinces are initially calculated. Non-parametric approaches using data envelopment analysis (DEA) is employed to compute the technical efficiency scores. In literature, both Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) are extensively used for efficiency analysis. We use DEA to compute the technical efficiency scores with following reasons. Firstly, SFA uses specific assumptions about the population distribution and will yield biased estimates if these fail to hold. Instead, DEA does not account for statistical noise and can be sensitive to outliers. In this paper,

no assumption is made with respect to the population distribution; the data are left to speak for themselves. Secondly, SFA relies on detailed information about the institutional characteristics, cost and price information in order to adequately specify a production function (Paxton, 2006). In the case where limited data on inputs, prices and costs are available, the DEA method is preferred. Furthermore, the productivity changes have also been studied by computing the Malmquist index, which is based on the DEA[6] approach as well.

We next use the efficiency scores obtained from the DEA approach to examine the convergence patterns. For this purpose, both parametric[7] convergence models and non-parametric ones are employed. As in Barro (1991), parametric convergence models mostly refer to the conventional neoclassical convergence approaches, such as β-convergence and σ-convergence.

These classical approaches fail to reveal some key features of the intra-distributional dynamics which might characterize the convergence process such as polarizations, stratifications or clustering of regions with similar patterns of local development. As argued by Pellegrini (2002), these approaches cannot effectively capture individual variability and heterogeneity and also hide phenomena which much concern some groups of regions, especially those located in the distribution tails. Quah (1997) suggests employing non-parametric distribution dynamics technique to study such mobility in order to determine the degree of convergence. Alternatively, the so-called γ-convergence can also be used for testing convergence dynamics. Eventually, several parametric and non-parametric convergence approaches are applied to assess whether a common trend in operational efficiency prevails across provinces.

7.4 Data

Our primary data sources are the China Statistical Yearbook and China Energy Statistical Yearbook. These are the main sources published by the National Bureau of Statistics China and used for energy related studies in China. Several studies have questioned the reliability and accuracy of economic statistics especially in an authoritarian economy. According to Chow (2006), China's economic indicators are for most part reliable and it is difficult for any falsifications of official statistical documents to happen. He especially

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[6]We use the SFA approach with the assumption of Cobb-Douglas production to calculate the efficiency scores in a preliminary version of the paper, and find the results (both efficiency scores and rankings) are highly correlated with those using DEA. Since this paper also studies the productivity changes and computes the Malmquist index, we use the DEA approach as the main body of the efficiency analysis. Besides, SFA models cannot directly estimate the Malmquist index (Pantzios et al., 2011).

[7]Bernard and Durlauf (1995) advocate another parametric convergence approach which studies the stochastic properties of a series. It differs from β-convergence since it does not look at the catching-up process but focuses on how persistent global shocks and variations among states can be. Stochastic convergence occurs if the series follows a trend stationary process. But since T is only 13, unit root test is not a viable option.

studies the Chinese GDP over the period 1996-2005. Koch-Weser (2013) also notes that there has been an improvement in the consistency of the Chinese statistics mainly due to both higher quality standards for data collection and anti-corruption measures.[8] We collected data for all provinces from 1996-2008. Our study relies on a balanced panel. Hainan and Tibet are excluded due to missing statistical data. However, none of them are large producers of electricity. Hence, we believe the final dataset used for the study is in good quality without hurting the coverage and representativeness.[9]

Table 7.1 shows the descriptive statistics of the economic indicators used in the paper, which are electricity generation, number of employees, transmission system losses (TSL), average household size, GDP share of industry sector, GDP share of service sector, real energy price index, real government consumption expenditure (in constant 1996 CNY) and the degree of government intervention. TSL can be due to both technical and non-technical reasons. Examples of technical losses are improper earthing at customer end, overloading of electricity mains, poor equipment standards, etc. Non-technical ones are illegal line tapping and connections, vandalization of equipment, non-payment by customers, etc. Government consumption expenditure is mainly indicative about the size of the government and may not adequately reflect the degree of intervention. Following Wei et al. (2009), the share of government financial expenditure in GDP is used as a proxy for the degree of government intervention. On average, the annual electricity generation growth rate accounts to 12.49%. Within the provincial sample, Qinghai and Heilongjiang have the highest and lowest annual growth rate of electricity generation, 41% and 5.2% respectively.

7.5 The efficiency-productivity analysis

The DEA technique employs piecewise linear programming to calculate the efficient or best-practice frontier. Assuming data are available on P inputs and M outputs for each of the D decision-making unit (DMU), the input and output vectors can be denoted by x_{it} and y_{it} respectively for the ith DMU in the tth time period. The data for all the DMUs can be denoted by $P \times D$ input matrix (X) and $M \times D$ output matrix (Y). An input-oriented DEA model is applied since the DMUs or Chinese provinces have more control over electricity inputs rather than outputs. Since the input quantities (particularly labor and capital are the major resources for production, the other two are also important since transmission loss reflects the levels of technologies, and government intervention providing information on the possibility to attract more investment from capital market) are the primary decision variables for DMUs in electricity generation, power utilities are bound by legal obligations to serve all clients in their respective provinces so they

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[8]We conducted "external consistency check" as suggested in Koch-Weser (2013) by comparing provincial GDP to provincial energy uses. There exists a relatively high correlation (more than 0.8) between the two, providing an evidence of data consistency.

[9]Hong Kong, Marco, Taiwan are excluded from the study of mainland China as usual.

Table 7.1: Annual Average of Economic Indicators used in the study from 1996 to 2008

Region	Electricity Generation (100 million kWh)	Number of Employees	Transmission System Losses	Household Size	GDP share of Industry Sector	GDP share of Service Sector	Real Energy Price	Govt. Consumption (100 million CNY)	Degree of Govt. Intervention
		(per 10,000)	(%)		(%)	(%)	Index		(%)
Beijing	173.497	4.896	19.048	2.762	34.915	62.154	112.76	234.945	17.791
Chongqing	219.878	5.679	12.369	2.98	42.662	40.115	109.302	136.945	13.889
Fujian	548.461	7.745	13.575	3.128	46.054	38.923	109.105	321.199	13.304
Gansu	363.642	6.634	8.611	3.652	45.454	35.508	122.849	111.54	15.593
Guangdong	1649.319	19.048	10.074	3.559	51.269	39.462	102.601	527.732	11.065
Guangxi	347.151	7.985	19.394	3.536	37.531	37.054	105.115	285.371	18.523
Guizhou	586.522	5.78	7.171	3.484	40.346	35.062	110.222	105.245	17.361
Hebei	1064.904	16.207	6.208	3.223	50.769	33.077	115.542	325.764	11.767
Heilongjiang	509.339	14.858	3.066	2.971	54.985	31.7	127.15	261.348	14.134
Henan	1079.758	21.075	7.735	3.379	49.738	29.8	111.754	415.408	13.35
Hubei	817.742	12.475	10.869	3.146	46.762	36.177	111.291	264.943	12.013
Hunan	477.12	10.81	17.216	3.155	40.162	38.162	114.318	357.097	14.908
Inner Mongolia	835.243	8.861	8.258	2.986	44.438	34.138	114.529	156.877	16.197
Jiangsu	1471.113	13.042	7.752	2.974	53.423	35.938	105.876	525.742	11.345
Jiangxi	290.057	9.233	10.195	3.374	42.785	35.523	111.167	170.074	12.876
Jilin	352.449	8.251	8.258	3.043	43.331	35.923	118.761	133.175	13.896
Liaoning	785.047	17.808	6.452	2.93	49.708	38.677	117.358	419.6	13.701
Ningxia	227.532	2.725	5.877	3.554	46.415	37.5	128.795	34.447	21.534
Qinghai	150.358	1.544	12.908	3.685	45.769	39.7	120.045	38.715	23.117
Shaanxi	429.529	8.634	8.052	3.368	47.031	37.554	113.006	224.376	12.519
Shandong	1488.724	19.759	8.258	2.887	52.315	34.123	104.974	1034.888	13.485
Shanghai	611.871	5.921	6.06	2.663	49.115	49.323	108.017	290.745	11.294
Shanxi	982.732	10.883	5.258	3.355	55.038	35.654	118.148	187.477	14.376
Sichuan	722.505	15.005	21.335	3.032	42.223	35.192	105.445	341.979	13.076
Tianjin	271.678	3.518	6.48	2.931	52.754	43.208	107.869	130.426	13.757
Xinjiang	241.717	5.442	7.329	3.411	42.985	35.777	133.508	166.769	20.652
Yunnan	444.528	7.083	20.412	3.56	43.662	35.315	116.667	148.52	17.771
Zhejiang	1010.517	9.617	9.287	2.79	53.269	37.415	103.458	810.31	13.887
Mean	644.521	9.972	10.199	3.196	46.529	37.658	113.438	288.703	14.801

may not be able to control outputs i.e. volume of power generated. According to Le Lannier and Porcher (2014), the adoption of an input-oriented framework is preferred for public utilities as demand can be seen as exogenous. We follow such routine and select input-oriented model in our analysis.[10]

The envelopment form of an input-oriented DEA with constant returns-to-scale (CRS)

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[10] Actually, given that linear programming cannot suffer from such statistical problems as simultaneous equation bias, the choice of an appropriate orientation is not as crucial as it is in the econometric estimation case. In fact, many studies tend to choose input orientation model for their analysis.

model can be denoted as follows:

$$\min_{\theta,\lambda} \theta,$$
$$s.t. :$$
$$-y_{it} + Y\lambda \geq 0,$$
$$\theta x_{it} - X\lambda \geq 0,$$
$$\lambda \geq 0 \tag{7.1}$$

where θ is the input TE score and λ is a $D \times 1$ vector of constants which reflects the linear combination of the ith DMU in the tth time period. If $\theta = 1$, then the DMU is said to be technically efficient. Efficiency scores from the DEA with variable returns-to-scale (VRS) model can also be computed by adding a convexity constraint $DI'\lambda = 1$ (where DI is a $D \times 1$ vector of ones) to equation 7.1. A fixed level of output and strong disposability in both inputs and outputs are assumed. The disposability assumption indicates that a rise in inputs does not result in a decline in outputs, and that any decline in outputs can still be produced with the same amount of inputs.

Choosing a model between the CRS or VRS model depends on the degree of control a utility has on the scale of its operations. If a utility cannot control its scale and is not operating at its optimal level, then the VRS model would be more appropriate (Nillesen and Pollitt, 2008). Factors such as labor shortage, oligopolistic competition and financial constraints can cause a sub-optimal performance. The VRS model does not account for size variation and compares utilities only within similar sample size. Utilities are not free to choose or adapt their size. Conversely, CRS models require an optimal operation level and the scale of such operation can be assumed to be under the control of the utilities (Hirschhausen von et al., 2006). If the Chinese utilities can adapt their sizes and scales of operation through mergers and by spreading fixed costs, then the CRS model is appropriate. This will allow them the possibility to adjust their sizes and scales of operation. For the sake of completeness both VRS and CRS models are applied in the paper.

When panel data are available, the most common approach in the DEA literature is to apply the Malmquist productivity growth index as outlined by Faere et al (1994). The index can be decomposed into technical efficiency and technical change indices. Technical efficiency arises when a DMU moves towards a given efficiency frontier while technical change occurs when a DMU moves to a new technically efficient frontier from period from period t to $t + 1$. We can also analyze how efficient province i is when using input x^{t-1} to produce y^{t-1} while comparing province using year t technology in year $t-1$. The Malmquist input-based index for a particular country can be defined as:

$$M_0(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\frac{D_0^t(x^{t+1}, y^{t+1})}{D_0^t(x^t, y^t)} \times \frac{D_0^{t+1}(x^{t+1}, y^{t+1})}{D_0^{t+1}(x^t, y^t)} \right]^{1/2}. \tag{7.2}$$

Changes in the Malmquist index can be attributed to either efficiency change of particular regions or shifts in the production frontier depicting technical change. Put differently, it allows us to disentangle, for a given province, a change in efficiency from a change in technology. Equation 7.2 represents the productivity of production point (x^{t+1}, y^{t+1}) relative to production point (x^t, y^t). D_0 denotes the distance functions from the frontier. If the Malmquist index is above unity, this will indicate positive productivity growth from period t to $t + 1$.

The selection of input and output variables for the DEA models is a crucial task. Similar to Yadav et al. (2009), we consider inputs such as number of employees, capital stock and TSL. It is also important to control for the influence of provincial governments in determining the differences in the level of investment and operation of electricity generation. As an extra input, real provincial government consumption expenditure is included. To some extent, it measures how much provincial governments can spend to intervene in the electricity market and affect the final investment and electricity generation. For the output, the electricity generation is used. Homogeneity of technology can be assumed across provinces.

Let K_{it} denotes the capital stock of a province i at time t and is estimated using the perpetual inventory method:

$$K_{i,t} = I_{i,t} + (1 - \delta_t)K_{i,t-1}, \tag{7.3}$$

with $K_{initial} = I_{initial}/(r_i + \delta_i)$, where I_{it} and δ_i denote real investment in the electricity industry (in constant 1996 values) and the depreciation rate of province i at time t respectively. $K_{initial}$ and $I_{initial}$ are initial capital stock and real investment in 1996 respectively. r is the long-run real investment growth rate. There is variation in selecting of the value for the depreciation rate in existing literature. Perkins (1998), Wang and Yao (2003 and Qian and Smyth (2006) all assume a rate of depreciation of 5%. We adopt this depreciation rate for our analysis.[11]

Table 7.2 shows the efficiency score, Malmquist index and ranking using above three models. The spearman correlation coefficient between DEA-CRS and DEA-VRS is about 0.88, which shows the results using both approaches are highly correlated. The ranking shows interesting results on the levels of energy efficiency across province. In general, it only illustrates the efficiency in the electricity generation and distribution industry across regions.

Three factors contribute to the major provincial differences. Firstly, resource abundant provinces tend to exhibit higher efficiency scores. For example Shanxi, which is rich in coal reserves ranks 1. Inner Mongolia, which is also a resource-exporting province,

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[11]We used different values for robustness check and the final results are similar to the ones reported in the paper.

Table 7.2: Annual Average Technical Efficiency Scores and Productivity Change Indices

Region	DEA-CRS		DEA-VRS		Malmquist	
	Score	Ranking	Score	Ranking	Score	Ranking
Anhui	0.6092	18	0.6677	20	0.6043	19
Beijing	0.3438	29	0.4808	28	0.3423	29
Chongqing	0.4377	26	0.5885	25	0.4459	26
Fujian	0.5862	21	0.6131	21	0.5927	21
Gansu	0.6062	19	0.7	18	0.6079	18
Guangdong	0.8646	8	0.9438	8	0.9016	8
Guangxi	0.4215	28	0.5069	26	0.4303	28
Guizhou	0.8746	6	0.9146	10	0.9366	6
Hebei	0.8723	7	0.8808	12	0.908	7
Heilongjiang	0.8485	10	0.9669	6	0.8474	10
Henan	0.7008	15	0.7108	16	0.7178	15
Hubei	0.5923	20	0.6085	22	0.5916	22
Hunan	0.4469	25	0.4692	29	0.454	25
InnerMongolia	0.9538	4	0.9708	5	0.9938	4
Jiangsu	0.9992	2	0.9992	4	1.0221	3
Jiangxi	0.4592	24	0.6008	23	0.4607	24
Jilin	0.6485	16	0.7054	17	0.6603	16
Liaoning	0.7815	12	0.7985	14	0.7817	12
Ningxia	0.9915	3	1	1	1.0488	2
Qinghai	0.7369	13	1	1	0.7406	13
Shaanxi	0.6192	17	0.6954	19	0.6227	17
Shandong	0.8608	9	0.9523	7	0.8658	9
Shanghai	0.9131	5	0.9385	9	0.9377	5
Shanxi	1	1	1	1	1.1293	1
Sichuan	0.4315	27	0.4915	27	0.4402	27
Tianjin	0.7285	14	0.9131	11	0.7319	14
Xinjiang	0.5808	22	0.7954	15	0.5933	20
Yunnan	0.5462	23	0.5946	24	0.5598	23
Zhejiang	0.83	11	0.8492	13	0.8349	11
Mean	0.6995	-	0.7709	-	0.7173	-

ranks 4 in DEA-CRS. Ningxia owns the sixth largest coal reserves in China and ranks in top 3 in all the three rankings. Since these provinces are close to the resource, the effects of economies of scale and economies of scope reduce capital investment and labor requirement for the extraction of resources for electricity generation. With the same level of output, these provinces enjoy higher productivity of inputs. The level of efficiency score and productivity index are relatively higher compared to other regions.

Secondly, the disparity in technology varies according to the economic level of the regions. Since most of the power plants are invested and operated by the government, advanced economies are able to invest more for efficient technologies. For example, Jiangsu, Shanghai and Guangdong are among the top in terms of GDP, they also ranked among the top in terms of efficiency as well, which shows developed regions can utilize their production by investing in efficiency improvement. This is because on one hand, these regions enjoy less government intervention (in terms of government consumption

expenditure), the negative effects of intervention is low and thus the government-initiated investments have less influence in these regions; on the other hand they are able to attract more investment from capital market which can be used for capacity expansion and technology advancement.

Thirdly, the size (or capacity) of the power sector also has positive impact on the efficiency level. Guangdong and Shandong are the top two provinces in terms of electricity generation, they are ranked in Top 10 in efficiency. Economies of scale in production reduces the production cost and indirectly improves the operational efficiency.

The only exception is Beijing[12] which is ranked 29 when computing the DEA-CRS efficiency scores and productivity indices. One explanation for this is that most of the administrative offices of the energy sectors are located in Beijing which is not related to the generation and distribution industry. These offices occupy physical capital investment and demand for labors from electricity sector and do not contribute to the pure productivity. We observe from the data that Beijing has high figures for labor and capital in the electricity sector and yet yields low electricity output. Nevertheless, we are not able to exclude this part from original data which results in lower rank of Beijing. The Malmquist index reflects similar patterns. As we can see from the table, Jiangsu, Ningxia and Shanxi have the score above 1, representing the significance of resource distance and economic level in determining the total productivity scores. The ranking using Malmquist index provides almost the same results as the ones using efficiency scores.

7.6 The convergence analysis

In this section we consider both parametric convergence models and non-parametric ones. As in Barro (1991), parametric convergence models mostly refer to the conventional neoclassical convergence approaches, such as β-convergence and σ-convergence. Non-parametric convergence models include distribution dynamics analysis and the so-called γ-convergence.

7.6.1 Absolute β-convergence

β-convergence hypothesis postulates efficiency convergence across provinces occurs if those provinces with low efficiency levels experience higher growth rates than the relatively more technically efficient ones. It can be absolute and conditional. Efficiency absolute convergence occurs if provinces with a low level of efficiency and those with a high efficiency level have similar determinants of efficiency steady state or long-run level, such

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[12]To check for the robustness of the DEA estimations, Beijing is removed from the dataset, and the efficiency and productivity scores are recomputed. No major difference is to be found and the DEA models do not seem to suffer from the influence of an outlier such as Beijing.

as physical and human capital stock, population growth, saving rate, etc., irrespective of the initial conditions. Thus, provinces with low efficiency levels will grow faster than those with high efficiency levels. All provinces will be converging to the same efficiency steady state level. Conditional convergence occurs when provinces converge to their own steady state level of efficiency instead of a common level, regardless the initial conditions. The lower the initial efficiency level relative to its steady state position, the faster will be efficiency growth rate. Such convergence happens due to diminishing marginal returns to capital as provinces with less initial capital per worker relative to their steady state will have greater returns on capital and so a higher rate of efficiency growth.

Following Barro and Sala-i-Martin (1992) the absolute or unconditional β-convergence hypothesis can be examined by estimating the following reduced-form equation for the pooled model:

$$\Delta \log RE_{i,t} = \zeta + \beta_a \log RE_{i,t-1} + e_{i,t},$$ (7.4)

where $RE_{i,t}$ denotes the relative efficiency (RE) of province i at time t. It captures $RDEAC_{i,t}$, $RDEAV_{i,t}$ and $RMALMQ_{i,t}$ variables, denoting the relative efficiency scores from the DEA-CRS, DEA-VRS and productivity growth models respectively. $RE_{i,t}$ is computed as the efficiency score of province i at time t divided by the sample average $\bar{RE}$ at time t. ζ is the constant term and e_{it} is the error term. Δ denotes the change in $RE_{i,t}$. $RE_{i,t-1}$ represents RE of province i in the previous period $t-1$ and is utilized as initial efficiency level to endogenize varying steady state of RE. β_a denotes the absolute convergence in efficiency. According to Islam (1995), $\beta_a = -(1 - \exp^{-\lambda\tau})$ where τ is the length of the period and λ is the speed of convergence, defined as speed at which a Chinese province move from its initial efficiency to the balanced efficiency growth or steady states. If the estimated β_a is negative and statistically different from zero, then absolute β-convergence hypothesis is supported. Chinese provinces with a low efficiency level are deemed to be growing faster than those with a high efficiency level while they are all converging to the same steady state or potential level of efficiency.

From equation 7.4, the half-life can be estimated from the β-convergence equation. It is the time needed to reach halfway of the steady state. The formulation can be applied as:

$$1 - e^{-\lambda\tau} = 1/2 \Rightarrow \tau = -(\ln(1/2))/\lambda = \ln 2/\lambda.$$ (7.5)

The delta method is utilized to compute standard errors of λ and half-life respectively. This indeed allows for a statistical assessment of the accuracy and precision of those computed values.

As shown in Table 3, the β_a coefficient is found to be negative and statistically significant at conventional levels. Provinces with a low efficiency level are deemed to be evolving faster than those with a high efficiency level and are all converging to a common level of

efficiency. The three models tend to yield a rather similar statistically significant λ value. The λ and half-life range from an annual 0.09 to 0.13 and 5.03 to 7.54 years respectively. Absolute β-convergence across Chinese provinces seems to be a fairly rapid process in terms of both electricity technical efficiency and productivity growth.

Table 7.3: Absolute β-Convergence Models

Coefficient	$\Delta \ln RDEAC_{i,t}$	$\Delta \ln RDEAV_{i,t}$	$\Delta \ln RMALMQ_{i,t}$
β_a	-0.122***	-0.105***	-0.088***
	(0.021)	(0.020)	(0.015)
ζ	-0.003	-0.002	0.0004
	(0.008)	(0.006)	(0.006)
R^2	0.092	0.07	0.094
Number of Observations	348	348	319
λ	0.131***	0.11***	0.092***
	(0.024)	(0.023)	(0.017)
Half-Life	5.31***	6.278***	7.541***
	(0.959)	(1.298)	(1.380)

The standard errors are in parenthesis.

***, ** and * denote 1%, 5% and 10% levels respectively.

7.6.2 Conditional β-convergence

Subsequently, conditional β-convergence can be studied by extending equation 7.4 to control for provinces with different steady states. The following reduced-form equation can be run as follows:

$$\ln RE_{i,t} = a + \beta_c \ln RE_{i,t} + \alpha_1 \ln H_{i,t} + \alpha_2 \ln M_{i,t} + \alpha_3 \ln S_{i,t} + \alpha_4 \ln P_{i,t} + \alpha_5 \ln G_{i,t} + f_i + \eta_t + \varepsilon_{i,t}, \tag{7.6}$$

where $H_{i,t}$, $M_{i,t}$, $S_{i,t}$, $P_{i,t}$ and $G_{i,t}$ represent average household size, GDP share of the industry sector, GDP share of service sector, real energy price index (constant 1996) and government intervention respectively of province i at time t. f_i denotes the province-specific fixed effects component which captures unobserved heterogeneity such as level of technology, managerial constraints, etc. η_t is a period-effect[13] component to control for specific temporal shocks such as decreasing quality-adjusted technological cost, increasing non-renewable raw materials costs, etc. a is the constant term and $\varepsilon_{i,t}$ is the error term.

A rise in average household size ($H_{i,t}$) will fuel electricity demand and therefore affect electricity efficiency adversely if there is limited access to the grid. Yet, such positive growth can also induce the deployment of fuel saving devices and lead to greater energy efficiency. Increased GDP share of both industry and service sector ($M_{i,t}$ and $S_{i,t}$) can be expected to influence relative efficiency positively as China has been moving up along the

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[13]The η_t component is usually excluded from the model as it tends to become irrelevant as τ increases.

development ladder from an agricultural-based economy towards an industrialized one. Despite the fact that China's manufacturing sector is renowned to be energy intensive, the energy consumption in the service sector is growing much faster over the last decade. The stringent energy efficiency policies in the service sector can contribute to a reduction in energy consumption and subsequently to a decline in energy intensity (Zhang, 2013). Rising energy price ($P_{i,t}$) can adversely affect efficiency as cost of input rises. Finally, government intervention ($G_{i,t}$) can cause a positive impact on efficiency and productivity especially with the implementation of policies to close of inefficient facilities and provide financial incentives for energy efficient investment. But if intervention is not efficient, then the upshot could be a decline in efficiency and productivity. Government intervention can be accompanied by a large government bureaucracy, rents for public employees and corruption (Acemoglu and Verdier, 2000). As a result, the impact of intervention can also be negative.

Conditional β-convergence occurs if $0 < \beta_c < 1$. Similarly we can also calculate the speed of convergence and the half-life for the conditional β-convergence models. As maintained by Islam (1995), the formula is now $\beta_c = e^{-\lambda\tau}$. λ measures the speed at which the efficiency of a Chinese province approaches its own steady state level. One crucial econometric issue to be considered before estimating using the above described models is endogeneity. Panel data models may yield biased estimates due to the correlation and endogeneity issues arising from the lagged dependent variable. Arellano and Bover (1995) and Blundell and Bond (1998) advocate the use of a system generalized method of moments (GMM) estimator which is designed for large N and small T. In our sample, both N and T are rather small. GMM estimators can be unstable when N is small and generate biased estimates for small samples. Furthermore, since T is small, the use of instrumental variables can be problematic. Kiviet (1995) proposes the use of the least squares with dummy variables bias-corrected (LSDVC)[14] version which is found to be quite accurate even when N and T are small.

The regression results are reported in Table 7.4. The coefficient β_c is generated by the LSDVC approach. Since $0 < \beta_c < 1$, conditional β-convergences of efficiency and productivity across provinces are confirmed. The λ and half-life range from a yearly 0.16 to 0.24 and 2.87 to 4.28 years respectively. The Chinese provinces are converging rapidly to their individual steady state efficiency level. GDP share of the industry have a significant and positive impact on relative technical efficiency. The industrial sector remains a major economic pillar for the Chinese economy and its expansion will enhance technical efficiency convergence. The average household size and the service sector are found to impact significantly and positively on total productivity change ($\ln RMALMQ_{i,t}$). As the increase in the average household size drives up demand, it also boosts the disposable income of the household. Energy saving devices can now be

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[14]One criticism of the LSDVC estimator is its failure to deal with the endogeneity of other explanatory variables apart from the lagged dependent one.

deployed and the access to grids can also be expanded. These will contribute to both the advancement of technical efficiency and technical change.

Table 7.4: Conditional β-Convergence Models

Coefficient	$\ln RDEAC_{i,t}$	$\ln RDEAV_{i,t}$	$\ln RMALMQ_{i,t}$
β_c	0.785***	0.807***	0.851***
	(0.017)	(0.057)	(0.011)
α_1	0.108	0.066	0.091***
	(0.100)	(0.083)	(0.028)
α_2	0.335***	0.134***	0.122
	(0.061)	(0.037)	(0.183)
α_3	0.268	0.169	0.094**
	(0.258)	(0.191)	(0.040)
α_4	-0.08	-0.029	-0.039
	(0.058)	(0.042)	(0.027)
α_5	-0.071*	-0.053*	-0.053***
	(0.043)	(0.031)	(0.010)
Number of Observations	319	319	290
λ	0.242***	0.214***	0.161***
	(0.021)	(0.070)	(0.013)
Half-Life	2.87***	3.244***	4.281***
	(0.255)	(1.063)	(0.349)

The standard errors are in parenthesis.

***, ** and * denote 1%, 5% and 10% levels respectively.

The degree of government intervention is found to have a negative impact on both relative efficiency and productivity growth, i.e. higher degree of government intervention lowers the relative efficiency level. This is in line with the concept of government intervention introduced by Acemoglu and Verdier (2000). One interpretation may be that the Chinese government expenditures have not efficiently been invested on cost-saving and updated technologies. In fact, following Fisher-Vanden and Ho (2007), the Chinese government has invested a large share of its capital unproductively in pursuit of non-economic objectives. Indeed, China still relies on coal-fired power plants which employs inefficient technologies and emit high amount of carbon dioxide. Furthermore, higher degree of intervention also restricts the inflow of foreign investment and sets barriers for technology transfer, which limits the advancement of technology not only in the electricity sector but also other industrial sectors.

Although energy price does have the expected negative sign, overall it has a statistically insignificant impact. There are several reasons which could explain this result. In an emerging economy, the demand for energy, particularly electricity is high in order to fuel the fast economic growth. However, the prices of energy are relatively low compared with other commodity goods. This is true in the case of China. The energy prices are fully controlled by the government. Even though the liberalization of the energy market starts 1990s, it is still far lagged behind of other market reform. The energy

prices stay far below the market prices and energy sectors enjoy the subsidies from the government. Hence, the prices would send a wrong signal to the market. Another reason for the insignificant effects of price may come from export growth. The export rises significantly and more than half of the energy demand increase in the period of 2002 to 2007 was to produce exported goods or service. Firms can make profits from production (or producing more in order to keep the same level of profits as before) even the prices of energy increase. Finally, even though the general demand of electricity decreases as the price of energy increase, the higher demand from the exporting firms drive up the electricity supply partly.

7.6.3 σ-convergence

Static efficiency dispersions among provinces can be studied by testing the σ-convergence hypothesis. This approach revolves around the cross-provincial standard deviation σ, over time trend. σ can simply be formulated as:

$$\sigma_t = \sqrt{(\frac{1}{N-1}) \sum_{i=1}^{N} (\ln EF_{i,t} - \ln \bar{EF_t})^2}, \tag{7.7}$$

where $EF_{i,t}$ is the efficiency score for province i at time t and $\bar{EF_t}$ is the mean value of efficiency scores at time t. If σ_t is following a downward trend towards zero, then σ-convergence of efficiency is supported. With respect to the Galton's Fallacy[15], the neoclassical β-convergence is a necessary but insufficient requirement for σ-convergence.

The σ-convergence results are presented in Figure 7.1. The σ of the all three RTE measures tends to exhibit a downward trend over time, although there seems to be a slight upward movement around 2002-2003.[16] As presented in Table 7.5, the RE measures have been experiencing a negative annual growth rate. These provide evidence of σ-convergence. Overall, the two neoclassical approaches confirm the notion of a β- and σ-type of TE convergence across the 29 Chinese provinces over the period 1996-2008.

7.6.4 Nonparametric distribution dynamics

According to Bianchi (1997), σ-convergence analysis alone is not sufficient to study convergence unless more information is gained on how units move within the distribution. As suggested by Quah (1997), we employ the non-parametric distribution dynamics technique to reveal the intra-distributional dynamics of the various provinces over time. Though this approach may offer a rough view of convergence, empirical regularities such

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[15] Barro and Sala-i-Martin (2004) provide a formal proof of the Galton's Fallacy.

[16] This upward rising is in line with many studies showing the rising of energy intensity between 2002 and 2005.

Figure 7.1: σ of Efficiency Indices

as persistence, polarization and club-formation[17] can be determined. The manifestation of convergence relates to a progressive budge towards a single-peak distribution whereby the probability mass will be concentrated around a certain value. Within the club-convergence concept, a twin-peak or multiple-peak distribution is equivalent to polarization or formation of club-convergence. Simply put, this is denotes divergence.

Let $\phi_t(x)$ be the cross-provincial distribution of a *RE* series at time t and the density at time $t + v$ for $v > 0$, is ϕ_{t+v} where y denotes *RE* level of a province at time $t + v$. Under the time-invariant process assumption, the link between $\phi_t(x)$ and $\phi_{t+v}(y)$ is:

$$\phi_{t+v}(y) = \int_0^{+\inf} f_v(y|x)\phi_t(x)dx, \tag{7.8}$$

where $f_v(y|x)$ is the conditional density of y. Assuming $q \in [x, y]$, and $f_{t,t+v}(q)$ designates

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[17]To a certain extent the concept of club-convergence can be related to conditional convergence where the latter allows for sub-groups to converge to a common steady state though the whole group may diverge. This approach differs from conditional convergence as initial conditions of individual countries are assumed to be the same. The formation of clubs takes place when for instance, two provinces with high and low efficiency relative to a certain threshold, have the propensity to build distinct groups at the same time as those with average efficiency are inclined to fade away. This may give rise to the process of polarization whereby provinces converge towards two distinct basins of attractions, resulting in the formations of clubs. Provinces with a low efficiency level do not catch up with those with a high level efficiency level if the initial conditions of similar steady state exist. These conditions will establish whether a province with a low level of efficiency gets caught in a development trap or will break free to match the performance of those provinces with a high efficiency level.

the joint distribution q, the joint distribution at point q_0 can be defined as:

$$f_{t,t+v} = \frac{1}{nh} \sum_{i=1}^{n} K(\frac{q_0 - q_i}{h}),$$ (7.9)

where $K(\cdot)$ is a bivariate kernel function assumed to follow the Epanechnikov function, $K(q) = (2/\pi)(1 - q'q)I$ with $q'q \leq 1$, where $I(\cdot)$ is the indicator function. Equation 7.9 describes the transition over one year from a given RE level in period t. It explains how the cross-provincial distribution at t evolves into $t+1$. The bandwidth h determines the degree of smoothness of the estimates. It is selected according to the cross-validation criterion (Nguyen Van, 2005). So, $\phi_t(x) = \int f_{t,t+v}(q)dy$ can be estimated. The conditional distribution is:

$$f_v(y|x) = \frac{f_{t,t+v}(q)}{\phi_t(x)}.$$ (7.10)

Convergence can be studied by computing the surface and contour of the conditional density $f_v(y|x)$ of equation 7.10 for the three relative efficiency scores as measured for DEA-CRS, DEA-VRS and Malmquist approaches. Figures 7.2, 7.3 and 7.4 present the snapshots of these distributions. With respect to the ln(RDEAC) and ln(RDEAV) series h is computed to be 0.935 and for ln(RMALQ), it is equal to 0.949.

As shown in Figures 7.2, the surface plot of ln(RDEAC) shows characteristics of nascent multi-peakedness and a tendency of club formations among provinces. The contour plot below represents the bird eye's view of the surface plot and indicates various levels of iso-probs i.e. the probability of a province moving between t and t+1. A peak below (above) the 45° line[18] implies a tendency for the Chinese provinces to have lower (higher) electricity efficiency. Club-convergence occurs when distinct peaks lie along this line. A major part of the probability mass is clustered along this line. A prominent peak with a proportion of 2% and relative technical efficiency of about 14 can be distinguished below from the diagonal line. Some provinces with high efficiency values tend to have a decreasing relative efficiency over time while the general tendency for the Chinese provinces is to remain in the same initial position. In this sense the technical efficiency convergence is only half-full or half-empty since the highly efficient provinces are "catching-up" with the low ones while the latter remain where they started.

Referring to Figure 7.3, a more or less similar pattern is observed with a multi-peak distribution of ln(RDEAV) where most of the peaks are found on the 45° line, implying again no signs of mobility among Chinese provinces. A few peaks in the lower tail of the distribution, especially those with relative technical efficiency scores less than zero, are found lying on the 45° line. Thus, inefficient provinces do not change from from their

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[18]The dotted diagonal 45° line represents persistence properties and illustrates the position of province i in the distribution which does not change from where it began. Any peak which is either above or below the diagonal line signifies a tendency for RTE to either increase or decrease respectively.

initial position. At the upper tail of the distribution, several peaks are found below the diagonal line, especially at relative efficiency levels of 6, 8, 10 and 13. Therefore, highly efficient provinces tend to have a decreasing relative efficiency over time. Once more, the technical efficiency convergence is found to be half-full or half-empty. Overall, no concrete evidence is found in support of the technical efficiency convergence hypothesis among Chinese provinces.

Figure 7.4 shows the distribution dynamics of relative productivity of ln(RMALMQ). As opposed to Figures 2(a) and 2(b), the surface plot shows a clear tendency towards a single ridge. As shown in the contour plot, a prominent peak with a proportion of 4% and relative productivity of about 2 which lies on the 45° line can be detected around the middle of the distribution. This rather implies some support for electricity productivity convergence.

To summarize, although some evidence of club-convergence is found, the above findings imply that the efficiency convergence hypothesis is only half-full or half-empty in the sense that technical efficiency does not converge for Chinese provinces while a persistence process on productivity is detected with a tendency towards convergence. The difference observed between trends in efficiency and productivity can be explained by technical progress included in the productivity analysis. Intensive technical progress moving towards advanced technologies is taking place with the development of the regional economy, which leads to the convergence tendency in productivity. Efficiency policies seem to have limited effects in most regions.

7.6.5 γ-convergence

For a reliable estimation of multivariate kernel densities, a large sample size is arguably required. This is due to the curse of dimensionality. It can be rather challenging to interpret distributions with dimensions higher than two especially when the number of observations is relatively small. Boyle and McCarthy (1997) propose an alternative measure known as γ-convergence to measure intra-distributional mobility over time. To test for γ-convergence, the binary version of the non-parametric Kendall's index of rank concordance (RCa) is calculated. The equation as proposed by Boyle and McCarthy (1997) is:

$$RCa_t = \frac{var(AR(EF)_{i,t} + AR(EF)_{i,0})}{var(2AR(EF)_{i,0})}, \tag{7.11}$$

where RCa_t denotes the RCa at time t. $AR(EF)_{i,t}$ is the actual rank of province i's efficiency at time t. $AR(EF)_{i,0}$ is the actual rank of province i's efficiency in the initial period 0. RCa_t captures the evolution of the ordinal ranking over a time interval and takes on a value between 0 and 1. The closer the value of the index is to zero, the greater the extent of intra-distributional mobility and as a consequence the greater the efficiency

convergence.

In Table 7.5, the reported average negative growth rates of both RCa and σ tend to be rather close, especially when referring to DEAC. In general, Figure 7.5 exhibits the trends for all RE series which are decreasing trend towards zero over time. The γ-convergence hypothesis is confirmed and this provides further evidence of efficiency convergence across the Chinese provinces.

Table 7.5: Annual Average Growth Rate (%) of σ and RC_a

Variable	σ	RCa
DEAC	-2.7049	-2.475
DEAV	-2.0972	-1.419
MALMQ	-3.1443	-1.0285

7.7   Policy implementation and concluding comments

This study has shed light on the convergence pattern of operational efficiency among 29 Chinese provincial electricity generations over the period 1996-2008. DEA method is exploited to compute the efficiency scores for each province. We then apply both parametric and non-parametric models to examine convergence patterns. Parametric convergence models confirm the prevalence of β-convergence and σ-convergence. These results are further supported by the non-parametric convergence models. Distribution dynamics reveals that technical efficiency convergence is only half-full or half-empty while some support for productivity convergence hypothesis is found. In addition, the γ-convergence hypothesis is found to hold. Overall, operational efficiency is converging across the Chinese provinces. The convergence both unconditional and conditional is related to four reasons: the fast growth of economy of all provinces; government policies towards energy saving and efficiency improvement, nationally and locally; the growing awareness of environmental concerns, not only government pressure but also public attention; the advancement of clean technologies and green energy resources.

Furthermore, since conditional β-convergence is found to be greater than the absolute β-convergence in terms of the speed of convergence λ, the operational efficiency of Chinese utilities is converging faster to their own efficiency steady state than to a common one. This outcome is encouraging for supporting the current policies at a provincial level even though it does not necessarily guarantee a steady state with higher efficiency level for the respective utilities. Put differently, there is still scope for active interventions and policy reforms from the government to boost the steady state at utility level. Nevertheless, as in Kostka and Hobbs (2012), not all local governments have achieved the national energy saving and emission reduction targets. Some regions' last minute response by energy

cuts and production limitation may harm not only the regional economy but also the public service. Local protectionism and individual interests can lead to a misalignment between central and local government in energy policies. For instance, a large amounts of small-sized power plants are inefficient and heavy polluters, but their revenues contribute to a significant part of local fiscal income. That is why the central government met resistance when it shut them down. Laws and regulatory system are needed to separate government departments from intervention.

Another example is that the central government develops the strategy of transmitting power from western to eastern China in order to balance such mismatch between electricity supply and demand. However, market, technical[19] and administrative barriers, and also the financial system between local and central authorities, impede the implementation of this strategy (Xu and Chen, 2006). Such barriers and local protectionism result in self-balance of supply and demand, which are a waste of resource. To overcome such barriers, the Scheme of the Reform for Power Industry started in 2002. Before 2002, more than half of the nation's capacity and 90% of transmission asset belongs to the State Power Corporation. Since the reform of power industry, the State Power was dismantled into five independent electricity generating and two transmission companies (Wang and Chen, 2012). The purpose of such division by the government is to foster competition in an attempt to improve efficiency and guarantee that inter-provincial trade of power can be implemented through market. However, according to Wang and Chen (2012) the state still owns more than 60% of total installed capacity by 2010.

Specifically, we also highlight several factors which can affect the energy efficiency and productivity both in the short- and long-term, pointing out the priorities to policymakers in tackling the difficulties in power sector reforms. The positive effect of household size provides evidence of economies of scale for electricity productivity growth. It is costly to build new grids and improve electrification penetration rate. Provinces can promote urbanization to exploit the economies of agglomeration. Because of concentrated economic activity and more dense population, utilities will benefit from large-scale electricity production with lower average cost of production and higher productivity. Low cost-operating utilities can also improve their productivity by taking advantage of the regional network. Urbanization speeds up the rate of industrialization of the Chinese economy. Industrial and service sector also contribute to the efficiency improvement as illustrated in our results. This is the "double dividend" from urbanization.

The price effects are insignificant. Our results suggest that energy price may not be contributing substantially to convergence of electricity productivity across Chinese

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[19]Most government investment in the power sector was biased towards generator installation; there has long been insufficient investment in grid construction. The dispatch and delivery network is less developed and so this limits the use of rich energy resources in western China to satisfy soaring energy demand in eastern regions, which aggravates the electricity crisis. In this regard, future investment should promote the unity of the national network. To achieve the energy and emission target, it is also necessary to increase interprovincial and inter-regional trading and power plant dispatch.

provinces. This is due to the opaque and economically irrational pricing system in China. Resources can be allocated effectively through the market if there is a sound price mechanism. Nonetheless, the electricity price was set administratively rather than decided by the supply-and-demand conditions. The National Development and Reform Commission (NDRC) determines the electricity prices based on the generation costs estimations. Adjustments to electricity prices are allowed, though not implemented properly.[20] A reform in electricity pricing system is one priority of the government concerns for the efficiency improvement.

In the latest 12th Five-Year-Plan, the reform toward reducing greenhouse gas emissions requires very large investment in renewable energy and energy efficiency. Grid expansions to accommodate the new mix of clean resources also require substantial investment. The negative effect of government intervention from the result suggests the government financial expenditures do not contribute to the improvement of efficiency. Accordingly, the government needs explicit policies for expenditures towards green technologies and efficiency advancement, for instance, introducing capacity payments or emission performance standard to quantify the output from new investment. However, generation and gird assets are mostly controlled or with policies influenced by the government. Inertia on strong government influence on the reform of the electricity market makes directing new investment to meet the long-term efficiency and environmental goals a big challenge.

The distribution dynamics study reveals some persistence process at play for relative inefficient provinces while the highly efficient ones tend to have a reduction in efficiency over time. One means of assisting the convergence process is to benchmark best practices, such as measuring a province's productive efficiency of electricity generated against a reference performance. In order for the provinces to keep track of their operational efficiency performance, it is imperative that the central government disseminates provincial-level data in both quality and quantity on a timely basis. This will enable provinces to smoothly track the evolution of their energy performances.

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[20]According to Ma (2011), the electricity prices have been adjusted only three times since 2004, despite the generation costs increase more than 10 times.

Figure 7.2: Surface and Contour Plots of the Conditional Function of the lnRDEAC from 1996 to 2008

Figure 7.3: Surface and Contour Plots of the Conditional Function of the lnRDEAV from 1996 to 2008

Figure 7.4: Surface and Contour Plots of the Conditional Function of the lnMALMQ from 1997 to 2008

Figure 7.5: *RCa* of Efficiency Indices

A Appendices

A.1 Appendix for modeling structures and parameters

This section presents the general modeling structure of the CITE model, including the nesting of production, energy aggregation, and consumption.

Figure A.1: Nested production function of regular sectors

Figure A.2: Nested production function of the energy sector

Figure A.3: Nested consumption function

A.2 Appendix for Chapter 3

A.2.1 Capital, innovation, and growth

The crucial model element is the endogenous growth characterized by new capital varieties. Investment can enhance the capital stock by inventing new blueprints (new varieties). The accumulation of sectoral capital has a positive effect on sectoral productivity and hence on sectoral growth.

$$Q = [\int_0^J x_j^\beta dj]^{1/\beta} \tag{A.1}$$

where $0 < \beta < 1$ and J is the number of intermediate varieties. With symmetric intermediates $x_j = x$ it can be simplified into:

$$Q = J^{\frac{1-\beta}{\beta}} X \tag{A.2}$$

where $X = J \cdot x$ for the aggregate output of the J-firms. $\frac{1-\beta}{\beta}$ reflects the gains from diversification (Bretschger and Ramer 2012).

In the benchmark case, we assume the economy follows the balanced growth path (BGP). We also assume the growth rate of factors (g_K) is lower than the economic growth (GDP growth). The difference between the two different growth rates is the gain from specialization which is created by innovation. Innovation extends the possibilities of production and hence requires less inputs to reach the same level of output in later time period, compared to the starting point.

Differentiating logarithmically both sides of equation (A.2), we have:

$$g_Q = \frac{1-\beta}{\beta} \cdot g_J + g_X \tag{A.3}$$

where $g_J = \frac{\dot{J}}{J}$ is growth rate of varieties, $g_X = \frac{\dot{X}}{X}$ is the growth rate of intermediate production, and $g_Q = \frac{\dot{Q}}{Q}$ is the growth rate of output.

Creating new varieties requires new capital which is used to cover the costs spent during innovation. Hence the growth rate of varieties in one sector is proportional to the growth rate of capital accumulation. Intermediate production requires factor inputs and energy input. All inputs for intermediate production are assumed to be at a lower rate, which leads to a lower growth rate for 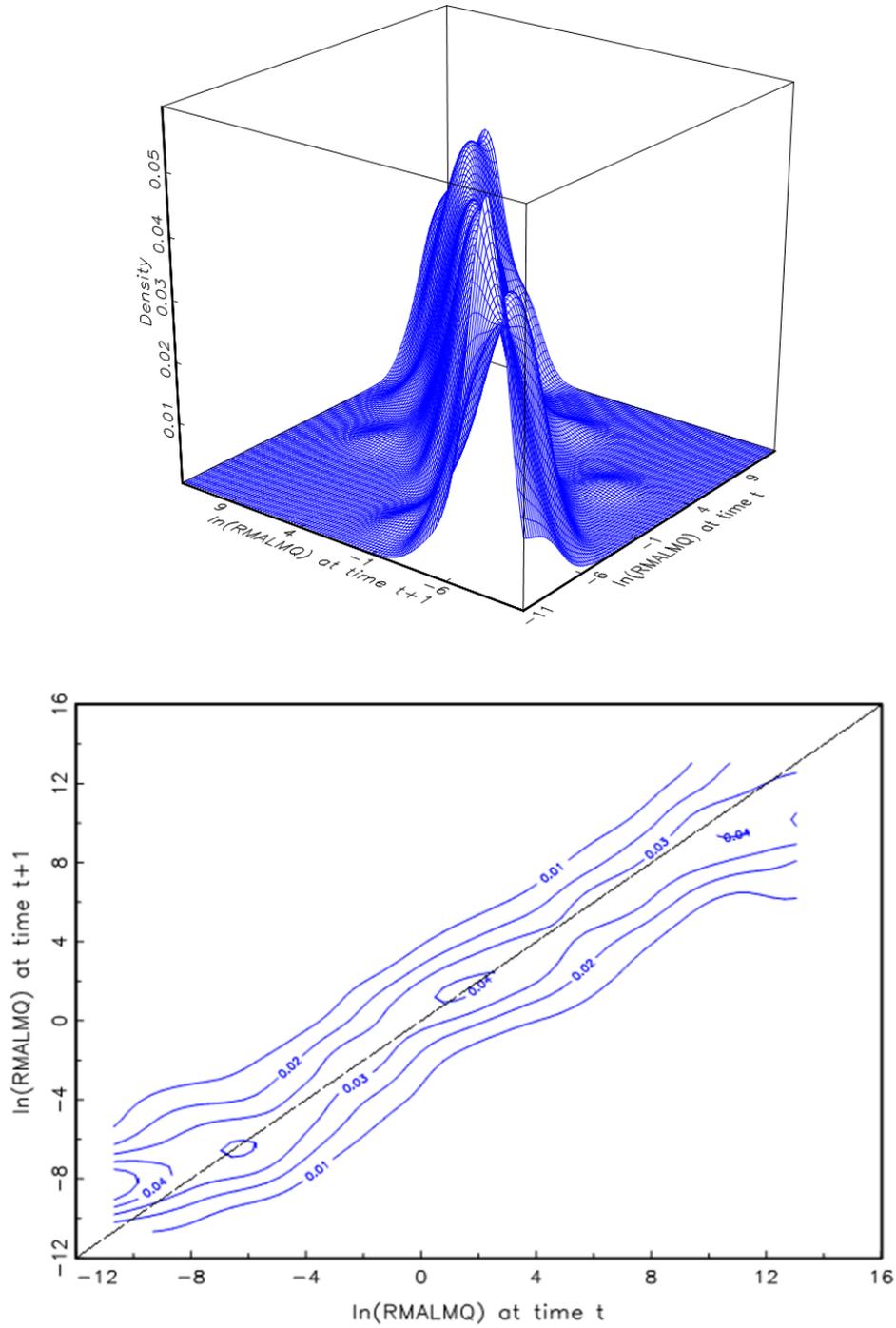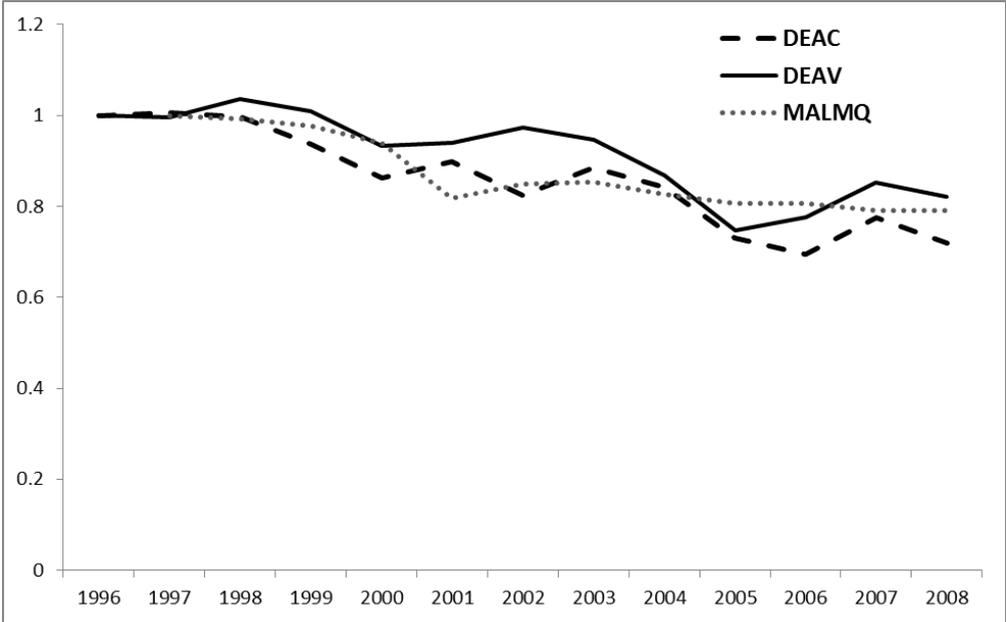intermediate production. From above, if we assume this lower growth rate for factors to be g_K, then $g_J = g_X = g_K$. The equation A.3[1] can be

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[1]The model is simulated in discrete time periods, hence the equation used in the model calibration is different compared with the one derived from continuous time case. In discrete time, equation A.2 can be expressed as follow: $Q_0(1 + g_Q) = [J_0(1 + g_K)]^{\frac{1-\beta}{\beta}} \cdot X_0(1 + g_K)$. Rearrange it we can obtain the discrete version for the relationship between growth rates: $g_Q = (1 + g_K)^{1/\beta} - 1$.

further simplified to

$$g_Q = \frac{1 - \beta}{\beta} \cdot g_K + g_K = \frac{1}{\beta} g_K \tag{A.4}$$

A.2.2 Values for controled parameters

Based on the above mentioned analysis, we choose different capital growth rates and capital shares to reflects information from new studies. The rates of interest and discount are selected to present different views for the future cost of energy policies. The growth rate of GDP then can be derived from equation A.4. In general, three groups of scenarios have designed to investigate the effects of energy transitions in the periods of 2012-2050: scenarios on capital growth (g_K), scenarios on innovation (β), scenarios on foresight (ρ). Details on the key parameters are illustrated in Table A.1.

Table A.1: Growth, innovation, interest and discount rate

g_K	$1 - \beta$	g_Q	r	ρ
1%	0.25	1.33%	1.41%	0.74%
1%	0.25	1.33%	2.73%	2.05%
1%	0.15	1.18%	2.65%	2.05%
1.5%	0.25	2.00%	1.96%	0.95%
1.5%	0.25	2.00%	3.07%	2.05%
1.5%	0.15	1.77%	2.95%	2.05%
2%	0.25	2.68%	2.50%	1.16%
2%	0.25	2.68%	3.41%	2.05%
2%	0.15	2.36%	3.25%	2.05%
2.5%	0.25	3.35%	3.35%	1.66%
2.5%	0.25	3.35%	3.74%	2.05%
2.5%	0.15	2.95%	3.54%	2.05%

A.2.3 Markov chain analysis of long-run growth

In this section, we present some evidence to show the robustness of sustainable growth for the Swiss economy. One of the famous methodologies in dynamic analysis is the Markov chain analysis. A Markov analysis looks at a sequence of events and analyzes the tendency of one event followed by another. It has been implemented in many fields. The first financial model to use a Markov chain was from Prasad et al. in 1974. Stockey and Lucas (1989) use it to analyze industry investment under uncertainty. Quah (1993) introduces Markov chain into convergence analysis. We apply this methodology to the convergence of economic growth and provide insights on the sustainable growth using historical data.

If we denote g_t as the distribution of GDP growth at time t, we also assume that the distribution follows a homogeneous, stationary, first-order Markov chain process. The

evolution of this discrete distribution can be written as follows:

$$g_{t+1} = M \cdot g_t \tag{A.5}$$

where M is the transition probability matrix which maps one distribution into another and tracks where in g_{t+1} points of g_t end up. This relationship reflects the economic growth of one period is only dependent on the last period, not how it was reached.[2]

Assuming that the transition probability matrix remains the same over time, the distribution after N periods can be obtained by iterating equation (A.5) N times, namely:

$$g_{t+N} = M^N \cdot g_t \tag{A.6}$$

As $N \to \infty$, the distribution converges to the ergodic distribution or the steady state distribution, g^{ss}, which can be characterized as:

$$g_{t+N} = M^N \cdot g_t \longrightarrow g^{ss} \tag{A.7}$$

Growth theory tells us there is a steady-state of an economy will converge to in the long-run. However, we do not know exactly what the level of steady-state growth rate will be. The ergodic distribution depicts the eventual long-run distribution of economic growth rate possibilities.

From data in IMF (2011), the average GDP growth of Switzerland since 1980 is about $\bar{g} = 1.50$. This value is larger than what we assumed in previous papers (Bretschger et al. 2011, 2012). Even though experienced global economic crisis since 2008, the average annual economic growth of Switzerland in the last five year is more than 2%.

We construct the economic growth into four states: depression (with $g < 0$), low growth ($0 \leq g < \bar{g}$), steady growth ($\bar{g} \leq g < 2\bar{g}$), and the peak ($g \geq 2\bar{g}$). By using above mentioned appoarch we are able to find the Markov transition matrix described in Table A.2. We find that when the economy experiences a depression, it is able to recover quickly and turn into low or steady growth with equal probability. Moreover, if the economy is in the state of low growth or steady growth, the probability of sustaining is high: 43% and 50%, respectively. In the long-run, the ergodic distribution shows that we can expect the Swiss economy to experience a favorite growth between 0 and 1.5% with the probability of 33%, between 1.50% and 3.0% with the probability of 35%. This result is in agreement with that of OECD (2012) estimate.[3] It also confirms that the scenarios we analyzed are plausible.

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[2]This is the propertity of Markov chain: memoryless

[3]OECD estimates that the average growth rate in GDP for Switzerland between 2011-2060 will be 2.1%. Even in per capital level, the growth rate is 1.7%, falling into the steady growth group in our analysis. OECD data are available in http://www.oecd.org/eco/outlook/lookingto2060.htm

Appendix A. Appendices

Table A.2: Markov transition probabilities and ergodic distribution

State	$g < 0$	$0 \leq g < \bar{g}$	$\bar{g} \leq g < 2\bar{g}$	$g \geq 2\bar{g}$
$g < 0$	0	**0.50**	**0.50**	0
$0 \leq g < \bar{g}$	0.29	**0.43**	0.14	0.14
$\bar{g} \leq g < 2\bar{g}$	0.17	0.17	**0.50**	0.17
$g \geq 2\bar{g}$	0.25	0.25	0.25	0.25
ergodic	0.19	0.33	0.35	0.14

A.3 Appendix for Chapter 4

This section shows some sensitivity analysis on elasticity of substitutions used in the numerical model. We vary the value of Armington trade elasticities η and elasticity of substitution between energy sources in intermediate production. The results are shown in Table A.3.

Table A.3: Aggregate effects when varying elasticity of substitutions

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

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

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

However, all these robustness check suggests that our cost estimation are stable in magnitude. The results are not very sensitive to the elasticities. Of course, we can run analysis for all other elasticities. As from our experience, the above two are the most relevant to this paper.

A.4 Appendix for Chapter 5

The following tables show the estimated accessibility intensity of Type B and C for sectors and regions.

Table A.4: Calculated weights representing the accessibility intensity of Type B spillover for region USA

	agr	trn	eis	man	ele
agr	-	0.03	0.95	0.01	0
trn	0	-	0.62	0.22	0.15
eis	0.12	0.58	-	0.07	0.24
man	0.01	0.57	0.28	-	0.13
ele	0	0.36	0.53	0.12	-
ors	0	0	0	0	0
col	0	0.36	0.53	0.12	0
oil	0	0.36	0.53	0.12	0
gas	0	0.36	0.53	0.12	0
cru	0	0.36	0.53	0.12	0

Table A.5: Calculated weights representing the accessibility intensity of Type B spillover for region CHN

	agr	trn	eis	man	ele
agr	-	0	0	0	0
trn	0	-	0.59	0.32	0.09
eis	0	0.69	-	0	0.31
man	0	1.00	0	-	0
ele	0	1.00	0	0	-
ors	0	0	0	0	0
col	0	1.00	0	0	0
oil	0	1.00	0	0	0
gas	0	1.00	0	0	0
cru	0	1.00	0	0	0

Table A.6: Calculated weights representing the accessibility intensity of Type B spillover for region $RA1$

	agr	trn	eis	man	ele
agr	-	0.02	0.91	0.07	0
trn	0.01	-	0.63	0.15	0.21
eis	0.08	0.66	-	0.07	0.18
man	0.03	0.53	0.28	-	0.16
ele	0	0.36	0.54	0.10	-
ors	0	0	0	0	0
col	0	0.36	0.54	0.10	0
oil	0	0.36	0.54	0.10	0
gas	0	0.36	0.54	0.10	0
cru	0	0.36	0.54	0.10	0

Table A.7: Calculated weights representing the accessibility intensity of Type B spillover for region ROW

	agr	trn	eis	man	ele
agr	-	0	1.00	0	0
trn	0	-	0.66	0.31	0.03
eis	0.05	0.71	-	0	0.23
man	0	0.66	0.19	-	0.16
ele	0	0.48	0.40	0.11	-
ors	0	0	0	0	0
col	0	0.48	0.40	0.11	0
oil	0	0.48	0.40	0.11	0
gas	0	0.48	0.40	0.11	0
cru	0	0.48	0.40	0.11	0

Table A.8: Calculated weights representing the accessibility intensity of Type C spillover for region USA

	EUR	USA	RUS	CHN	IND	RA1	ROW
agr	0.28	-	0.15	0.08	0.05	0.17	0.28
trn	0.30	-	0.20	0.10	0.09	0.18	0.13
eis	0.32	-	0.11	0.10	0.13	0.19	0.14
man	0.31	-	0.08	0.13	0.11	0.21	0.17
ele	0.26	-	0.17	0.11	0.17	0.15	0.14
ors	0	-	0	0	0	0	0
col	0.26	-	0.17	0.11	0.17	0.15	0.14
oil	0.26	-	0.17	0.11	0.17	0.15	0.14
gas	0.26	-	0.17	0.11	0.17	0.15	0.14
cru	0.26	-	0.17	0.11	0.17	0.15	0.14

Appendix A. Appendices

Table A.9: Calculated weights representing the accessibility intensity of Type C spillover for region RUS

	EUR	USA	RUS	CHN	IND	$RA1$	ROW
agr	0.14	0.53	-	0	0	0.33	0
trn	0.07	0.08	-	0	0	0.13	0.71
eis	0.45	0.35	-	0	0	0.20	0
man	0.13	0.11	-	0	0	0.12	0.64
ele	0.30	0.54	-	0	0	0.16	0
ors	0	0	-	0	0	0	0
col	0.30	0.54	-	0	0	0.16	0
oil	0.30	0.54	-	0	0	0.16	0
gas	0.30	0.54	-	0	0	0.16	0
cru	0.30	0.54	-	0	0	0.16	0

Table A.10: Calculated weights representing the accessibility intensity of Type C spillover for region CHN

	EUR	USA	RUS	CHN	IND	$RA1$	ROW
agr	0.09	0.22	0	-	0	0.13	0.56
trn	0.09	0.12	0	-	0	0.14	0.66
eis	0.07	0.08	0.37	-	0.14	0.09	0.25
man	0.11	0.11	0.12	-	0.09	0.15	0.41
ele	0.12	0.15	0	-	0	0.34	0.39
ors	0	0	0	-	0	0	0
col	0.12	0.15	0	-	0	0.34	0.39
oil	0.12	0.15	0	-	0	0.34	0.39
gas	0.12	0.15	0	-	0	0.34	0.39
cru	0.12	0.15	0	-	0	0.34	0.39

Table A.11: Calculated weights representing the accessibility intensity of Type C spillover for region $RA1$

	EUR	USA	RUS	CHN	IND	$RA1$	ROW
agr	0.34	0.24	0.26	0.02	0	-	0.13
trn	0.30	0.23	0.12	0.16	0.03	-	0.16
eis	0.28	0.22	0.22	0.09	0.06	-	0.13
man	0.28	0.24	0.20	0.09	0.02	-	0.17
ele	0.30	0.24	0.14	0.11	0.08	-	0.12
ors	0	0	0	0	0	-	0
col	0.30	0.24	0.14	0.11	0.08	-	0.12
oil	0.30	0.24	0.14	0.11	0.08	-	0.12
gas	0.30	0.24	0.14	0.11	0.08	-	0.12
cru	0.30	0.24	0.14	0.11	0.08	-	0.12

Table A.12: Calculated weights representing the accessibility intensity of Type C spillover for region IND

	EUR	USA	RUS	CHN	IND	$RA1$	ROW
agr	0.08	0.20	0	0	-	0.08	0.64
trn	0.02	0.14	0	0.52	-	0.10	0.22
eis	0.13	0.19	0	0.40	-	0.13	0.15
man	0.10	0.16	0	0.59	-	0.06	0.09
ele	0.07	0.10	0	0.56	-	0.22	0.05
ors	0	0	0	0	-	0	0
col	0.07	0.10	0	0.56	-	0.22	0.05
oil	0.07	0.10	0	0.56	-	0.22	0.05
gas	0.07	0.10	0	0.56	-	0.22	0.05
cru	0.07	0.10	0	0.56	-	0.22	0.05

Table A.13: Calculated weights representing the accessibility intensity of Type C spillover for region ROW

	EUR	USA	RUS	CHN	IND	$RA1$	ROW
agr	0.05	0.09	0.23	0.24	0.22	0.18	-
trn	0.05	0.09	0.03	0.35	0.29	0.19	-
eis	0.09	0.13	0.05	0.26	0.19	0.28	-
man	0.08	0.14	0.13	0.17	0.13	0.35	-
ele	0.07	0.13	0.18	0.29	0.02	0.30	-
ors	0	0	0	0	0	0	-
col	0.07	0.13	0.18	0.29	0.02	0.30	-
oil	0.07	0.13	0.18	0.29	0.02	0.30	-
gas	0.07	0.13	0.18	0.29	0.02	0.30	-
cru	0.07	0.13	0.18	0.29	0.02	0.30	-

A.5   Appendix for Chapter 6

In the appendix, we present the results of models which consider the endogeneity issues. We follow the procedure of Terza et al. (2008). In the first stage, the endogenous variable is regressed against instrumental as well exogenous variables. In the second stage, the original equation is estimated by including the residuals obtained in the first stage. We include the residuals in both MREM and MTREM.

The instruments considered in our empirical analysis are the ratio of engineers in professional personnel (ENG_{it}), the number of secondary schools (SCH_{it}) and the number of teachers (TEA_{it}). In order to verify the validity of the instruments, we estimate a regular fixed effects model. To test for weak instruments we compute the Cragg-Donald Wald F test statistic. The value of this statistic (12.21) is larger than the critical value at 10% level of significance (9.08) suggested by Stock-Yogo (2003). Therefore, we reject the hypothesis that instruments are weak. The Hansen J statistic for testing the overidentification of all instruments does not reject the null hypothesis of valid instruments (Chi2(2)=0.50, P-Value=0.78). All these results show that we were able to find reasonable instruments. Further, the endogeneity test rejects the null hypothesis of exogeneity of GDP (Chi2(1)=7.07, P-Value=0.01). All tests show that the instruments are reasonable for our analysis.

The estimation results are presented in Table A.14. The sign and magnitude of all estimated coefficients are the similar to the results in Table 6.3. As for estimated efficiency levels, the rank correlation coefficient between the level of efficiency obtained using MREM and MREM-2SRI is 0.9951. Also, the rank correlation coefficient between the level of efficiency obtained using MTREM and MTREM-2SRI is very high (0.9749).

Table A.14: Model results if considering endogeneity

Variable	MREM-2SRI	MTREM-2SRI
P	-0.000	-0.000
	(0.000)	(0.000)
Y	0.871***	0.881***
	(0.123)	(0.129)
Residual of Y	-0.125	-0.135***
	(0.088)	(0.038)
HS	-0.400***	-0.439***
	(0.103)	(0.048)
HD	-0.125***	-0.170***
	(0.020)	(0.006)
POP	0.184**	0.194***
	(0.089)	(0.023)
HCDD	-0.003	-0.003
	(0.006)	(0.003)
BUS	0.073**	0.068**
	(0.036)	(0.032)
CAR	0.046*	0.046**
	(0.027)	(0.022)
SSH	-0.007***	-0.006***
	(0.003)	(0.001)
ISH	0.000	0.001
	(0.003)	(0.002)
T	-0.004	-0.005
	(0.015)	(0.020)
T2	-0.002***	-0.002***
	(0.001)	(0.001)
M(P)	0.006*	0.014***
	(0.003)	(0.001)
M(Y)	-0.748***	-0.620***
	(0.124)	(0.119)
M(BUS)	0.194	-0.007
	(0.123)	(0.038)
M(CAR)	0.277***	0.299***
	(0.101)	(0.024)
M(ISH)	0.013***	0.012***
	(0.004)	(0.001)
Constant	4.498***	1.356***
	(1.412)	(0.396)
Log likelihood	372.1	366.2

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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