A By-production Approach to Studying Environment-constrained Technical and Allocative Inefficiencies and Measuring Marginal Abatement Costs: the Case of China's Provinces

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature...

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Abstract

This thesis employs the by-production approach to modelling pollution generating technologies to investigate production and environmental efficiencies, design consumption-increasing and emission non-increasing input policy reforms, and derive a measure of marginal abatement costs in the case of China.

The second chapter introduces by-production approach to modelling the pollution generating technologies. It decomposes a general pollution generating technology as classical intended production technology and nature's residual-generation mechanism. In this chapter, some production and environmental efficiency indexes will be extended and applied under by-production approach to study China's regional technical efficiency incorporated emission generation. According to our estimation results, some reasons analysis and policy implementation suggestions are given.

The third chapter co-authored with Professor Sushama Murty proposes a model that gives a key role to the energy sector, and gives a theoretical characterisation for the existence of feasible, consumption-increasing, and emission-non increasing input policy reforms at the status-quo of a national or a sub-national economic unit. A methodology is developed to empirically test for the existence of such efficiency-improving reforms. Formulae to compute the optimal efficiency-increasing reform and a measure of marginal abatement cost (MAC) based on local policy reforms using data available at the status-quo are derived.

The fourth chapter co-authored with Professor Sushama Murty implements the methodology developed in the third chapter to test the existence and to study the structure of efficiency-improving reforms using data on thirty provinces in China. A new class of limitational variable elasticity of substitution (LVES) production functions for specifying technologies of the energy-using and energy-generating sectors is introduced and two such production functions are estimated along with the conventional Cobb Douglas and

CES production functions. MACs and the optimal efficiency-improving reforms are found to be sensitive to the choice of the production functions employed. There is a huge variation in MACs across provinces. The optimal efficiency-improving reform encourages a substitution from coal-fired electricity generation to gas-fired electricity and renewable energy generation for all provinces.

The fifth chapter reviews China's regional variations in electricity generation, primary energy usage, and forest cover. To better understand the China's carbon emission control policies, we also briefly introduce the carbon emission scheme implementation. Based on these information, we incorporate the efficiency-improving reforms and MACs estimated in the fourth chapter to analyse the direction of input resources reallocation and give further recommendations for each province.

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Abbreviations

BP	By-production Approach
CNY	Chinese Yuan Renminbi
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
FGL	Färe-Grosskopf-Lovell Efficiency Index
HYP	Hyperbolic Efficiency Index
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOG	Levelized Costs of Generating
lpcap	Local Proportional Changes in Active Policies
LVES	Limitational Variable Elasticity of Substitution
MAC	Marginal Abatement Cost
MTA	Motzkin's Theorem of Alternative
Mtoe	Million Tons of Oil Equivalent
riap	Reform in Active Policies
USD	US Dollor
WD	Weak-disposability Approach

Chapter 1

Introduction

1.1 Background

As a middle-income country with a rapidly developing economy, China is facing a series of environmental challenges. Searching for more effective methods to solve the growing environmental problems has become a vital task of the Chinese government in recent years. However, the high level of air pollution, water resources scarcity, and the growth of energy demand are still prominent, which influences public health and restricts social development. Based on the "State of the Environment Report" (SOER) issued in 2014, around 59.6% out of a total 4,778 groundwater resources in China have been monitored and rated as having poor and very poor quality and, the proportion of excellent quality resources is only 10.4%.[1] Furthermore, the air pollution in China is also very serious. The SOER also indicates that around 10.6% of the land area has suffered from acid rain, and these areas are mainly located in the Yangtze River basin and southeastern areas.[2] Meanwhile, according to the statistics of 74 key cities monitored according to the new ambient air quality standards, only three cities met the air quality standard and 95.9% cities exceeded the standard in 2012.[3] Moreover, the average number of days with haze in 2013 reached 35.9, and 18.3 days more than the number in 2012, topping the figure since 1961. Due to the increasingly close relationship between China and the rest of world, Chinas current environmental issues are also matter of concern for other countries. Based on the International Energy Agency (IEA)'s estimates, China became the largest

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[1] SOER is an annual report issued by Chinas Ministry of Environmental Protection.

[2] Yangtze is the world's third largest river. The 1.8 million square kilometer area of the Yangtze River Basin is home to 480 million people, and supports around half of the total wild animals and plant species in China. Due to its important place in the ecosystem, the World Wide Fund for Nature (WWF) designated the Yangtze River basin as one of the 35 priority areas amongst the Global 200 Ecoregions (G200).

[3] The new ambient air quality standards were issued Chinas Ministry of Environmental Protection and State Administration for Quality Supervision and Inspection and Quarantine in 2012. 74 designated scale cities were listed as the first phrase of implementation. SOER shows that only Haikou, Zhoushan and Lhasa three out of 74 cities complied with the new air quality standards in 2013.

emitter of greenhouse gases in 2005.[4] By 2007, China was also known as the largest energy related carbon dioxide (CO_2) emitter. Olivier et al. (2012) also indicate that due to around three quarters of China's CO_2 emissions caming from fossil fuel combustion and the increasing recent demands on energy utilisation, China's growing trend in CO_2 emissions will continue.

In 1973, the Chinese government promulgated the "Trial of industrial waste discharge standards", tentatively determined the emission standards of 13 categories of hazardous substances, and brought the various regions of industrial emissions into the focus detecting objects. Figure 1.1 illustrates the emission trend of industrial waste gas (in 100 millions of cubic metres), waste water (in ten thousands of tons), and solid waste (in ten thousands of tons) generated from 1995 to 2012.[5]

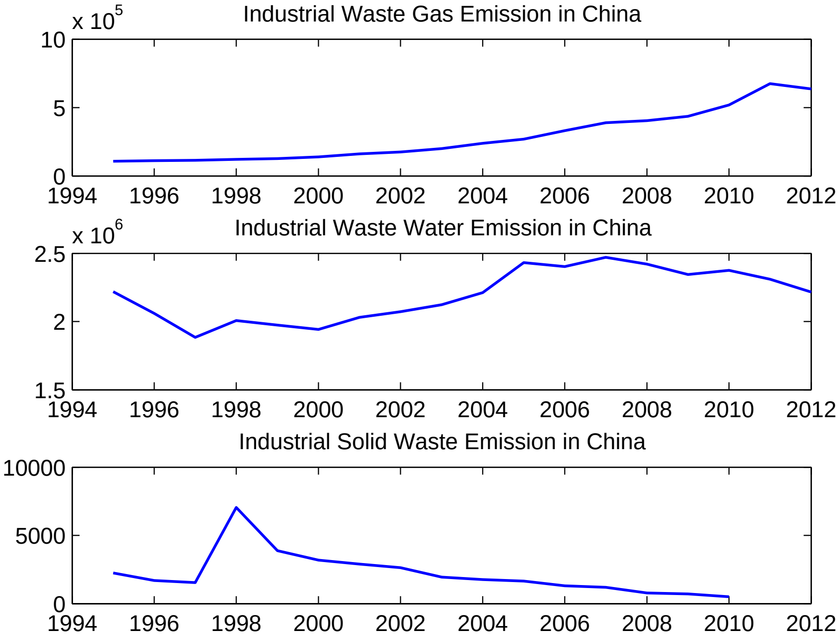

Figure 1.1: Industrial Waste Emissions in China

According to Figure 1.1, the industrial waste gas increased over the period. Meanwhile,

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[4] A greenhouse gas (sometimes abbreviated GHG) is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. (Intergovernmental Panel on Climate Change (IPCC)). The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.

[5] All data source come from the National Bureau of Statistics of China. The solid waste emission data is available until 2010.

waste water also had an increasing trend from 1997 to 2007 but after 2007, the upward trend was controlled, and thus it decreased. In contrast, the emission of solid wastes showed a continuously decreasing trend after 1998. Even though the industrial pollution abatement seems like to be improving in China now, the current pollution situation is still very grim, especially for waste gas and waste water. Hence, how to further improve pollution control, and how to adopt appropriate policies to encourage pollution control efforts in the future still remain a long path of exploration for China.

The increasingly serious environmental problems might reflect a consequence of rapid industrialisation in China. Unconstrained expansion of energy intensive industries have created a high dependence on dirty coal and imported oil, meaning that environmental problems might get worse or more expensive to address the longer they are unresolved.[6] Despite the mode of economic development in each province varying, environmental pollution and expected future natural resource shortages become a major concern among most provinces in China. In this work, we would like to take China as the research objective and make an effort to understand the critical environmental issues resulting from the China's regional economic growth (e.g., sub-country production and environmental efficiencies, efficiency improving reforms, and shadow price of CO_2 etc.), and to use this information to provide valuable suggestions to policy makers and economic units.

1.2 Motivation

In order to solve the emission issues, it seems necessary to capture how emission could be generated in production process and how to link emission to other outputs, and inputs. This thesis was initially inspired by the description of pollution generating process. It is worth noting that, since the pollution is regarded as a residual or byproduct of the production process (Ayres and Kneese, 1969), the question about how to better monitor and evaluate such pollution generating production with environmental requires consider-

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[6] China is currently the worlds largest coal producer and consumer and has accounted for about half the worlds coal consumption since the early 1980s. According to US EIA's report, China also became the largest global net importer of oil in the first quarter of 2014. Source from: `https://www.eia.gov/beta/international/analysis.cfm?iso=CHN`

ation should be undertaken. This study will focus on the production side of the economy. Thus, the main questions about adjusting standard technical efficiency measures incorporated environmental concerns, and investigating allocative efficiency including factors of the production structure such as energy input and emission mitigation efforts will be addressed from the view of theories and applications in pollution generating technologies.

In recent literature, the development of activity analysis enables methods integrating environmental aspect into production efficiency evaluation only link to quantity information, and the evaluation methods based on non-parametric programming do not require the specification of a production function form. Hence, such methods offer a large range of possibilities due to the flexibility and the less restrictive assumptions inherent in relation between inputs, desirable outputs and undesirable outputs (e.g. pollution) (Dakpo et al., 2016). Follow the recent development of modelling pollution-generating technologies, Dakpo et al. (2016) also review the different pollution generating technologies to formalise the implicit relation between pollution and desirable outputs. The first one is input approach. Behind this approach, emission of environmentally detrimental products are treated as the use of environmental capacity for disposal. Hence, Baumol and Oates (1988) and Cropper and Oates (1992) treat emissions as ordinary inputs of production that satisfies free disposability. However, Førsund (2009, 2016) argues the input approach is convincing at a macro level where a single relation with residuals as inputs may be regarded as reduced form of large system, but at a micro level such treatment inevitably leads to zero production of bad output for producer being a economic unit, and the idea of input approach has also been challenged as it deflect from physic laws and material balance principle.[7] The second one refers to the "weak-disposability" approach attributed to Shephard (1970) and Färe (1988), which indicates that the disposability of bad output is not free, and at least bad outputs could be disposed off in proportion to the good outputs, and if no bad output is generated, no good outputs will be produced.[8] In related empirical studies, the non-parametric and parametric specifications of the weak-disposability approach are widely used to construct the technical efficiency measurements. However,

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[7] The material balance principle explains the crucial role of material inputs in generating residuals of production process, which is firstly proposed by Ayres and Kneese (1969).

[8] *See*, e.g. Coggins and Swinton (1996); Färe et al. (1989, 1993, 2005); Grosskopf (1996)

Førsund (2009, 2016) points out the assumption of weak-disposability by using single trade-off between desirable and undesirable outputs is still in conflict with the material balance principle even abatement is explicitly introduced. Murty et al. (2012) indicate the property of the weak-disposability approach might result in counterintuitive implications for trade-offs between inputs, good outputs and bad outputs. Hence, they also propose the other "by-production" approach based on the idea of multi-equation approach from Frisch (1965); Førsund (1972, 1973, 2009), which decomposes the conventional pollution generating technologies as two technology sets to correct the counter-intuitive trade-offs arising in the weak-disposability approach.[9] They also propose efficiency indexes to measure efficiency of producing units generating both the good and bad outputs in the context of by-production. Hence, we will adopt the by-production approach to modelling emission generating technologies to measure China's province-level technical efficiency in Chapter 2 of this thesis.

Furthermore, the by-production approach distinguishes between emission causing (e.g. fossil fuels) and non-emission causing inputs (e.g. labour and capital), such distinction was firstly mentioned in Ayres and Kneese (1969). It also models the pollution generating technologies as an intersection of two technology sets. One describes the standard transformation from all inputs to desirable inputs, while the other one defined by the relationship between emission causing inputs and emission generation, and emission mitigation made possible by human abatement efforts. Therefore, such approach is also quite consistent with the guidelines laid down in IPCC (2006), where emission factors for each type of fossil fuel are provided indicating a linear relationship between emission and fossil fuels use, and carbon sequestration factors for the relationship between carbon mitigation and afforestation. Murty (2016) proposes a model that includes factors of the production structure such as energy from fossil fuels and renewable resources, and emission mitigation efforts, etc. to investigate if there exists the optimal input allocation (allocative efficiency improvement) for the promotion of both economic and environmental objectives (e.g., increasing profits and reducing emission), and to derive explicit formulae for computing the marginal abatement costs (MACs) by using data prevailing at the status-

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[9] *See*, e.g. Murty et al. (2012); Murty (2015b)

quo.

The computation of the MACs, in most of the existing literature, is based on the assumption of maximisation of the economic objectives of economic units subject to environmental and institutional constraints. However, it will not always be the case that the current status-quo of economic units is a result of optimising behaviour. Moreover, the movement from an inefficient status-quo attaining the optimum may require big changes in the existing fiscal and political systems, hence, the implementation of required big changes in policy instruments tends to be "slow and piecemeal" (Murty, 2015a). Murty (2016) also defines a measure of MAC as a reduction in the maximum final profit per unit reduction in its current emission level, which can be achieved by small changes in policy variables that lead to allocations that lie in a local neighbourhood of the status-quo of an economic unit. We refer such analysis as the policy reforms methodology. The concept of policy reforms is motivated and influenced by the tax reform literature and the second best taxation theory in public economics.[10] In Chapter 3, we will adopt a by-production approach and input policy reforms to design a theoretical framework to test for the existence of allocative efficiency improving reforms, which are final consumption increasing and emission non-increasing. The computation of optimal efficiency improving policy reforms and MAC are also derived based on the local reforms.

In the construction of the intended output production, the role of energy can be summarized as follows. Firstly, it is an essential input of desirable output generation. Secondly, there are limits to increasing desirable outputs when energy input is fixed even if the other inputs increase arbitrarily. Lastly, increasing the usage of energy requires a concomitant increase in other inputs, hence the energy utilisation is highly complementary with other input use. Furthermore, due to energy being obtained from many resources, changing energy resources from fossil fuels to renewable resources might lead to emission mitigation effect. Hence, in Chapter 4, we would like to incorporate the energy features discussed above to present some relevant axioms and construct the specific energy production and intended output production functional forms for representing technology sets.

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[10] See, Feldstein (1976); Guesnerie (1977) and Diamond and Mirrlees (1971), etc.

Based on China's province-level data prevailing at the status-quo, theoretical methods to study scope for efficiency improvement and computation of MAC in the third chapter can be employed to investigate China's energy utilisation and related environmental issues.

1.3 Thesis Structure

This introductory chapter aims to outline the broader context and structure of this thesis. Chapter 2 provides the measurement of production efficiency and environmental efficiency in China's province-level under the by-production approach. Chapter 3 introduces a theoretical methodology to design final consumption-increasing and emission non-increasing input policy reforms and derive explicit formulae to compute the optimal policy reforms and marginal abatement costs. Chapter 4 employs the theories in the third chapter to empirically test the existence of China's regional inputs allocative efficiency improvement and compute the regional marginal abatement costs using China's province-level data prevailing. Chapter 5 can be regarded as an extension of Chapter 4, where the regional profile of energy utilisation, forests and some environmental policies are discussed for each province based on the results of Chapter 4. Chapter 6 concludes this thesis and suggests future studies.

Chapter 2

Measurement of Regional Production and Environmental Efficiency in China: A By-production Approach[1]

2.1 Introduction

From the point of modern environmental economists, pollution generation seems to be a residual associated with the processes of production and consumption. Ayres and Kneese (1969) proposed the phrase "*material balance*" to explain such process about inputs as fuels, raw materials to economic system are partly converted into final goods and partly transformed into residual wastes. Hence, the concept of material balance underlines the inevitability of residuals as by-products generation when material resources are employing. According to the key feature of joint production of intended outputs and unintended residuals (by-products), the modelling environment and economic interactions should capture the relation between intended outputs and unintended outputs in pollution generating technologies.

In conventional production theory, one of the conventional measures to evaluate production performance is efficiency. According to Koopmans (1951), a production unit is efficient if it operates on the frontier of its technology. Lovell (1993) also defines the efficiency of a production unit in terms of a comparison between the observed and optimal values of its output and input. In particular, the comparison can take the form of the ratio of the observed to maximum potential output from the given level of input, or the ratio of the minimum potential to observed input required to produce the given level of output. Therefore, two traditional efficiency measures input-oriented and output-oriented were introduced by Debreu (1951) and Farrell (1957), based on the radial contraction of all

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[1] Paper based on this chapter has been published by *Environmental Economics and Policy Studies* in August 2016. Available at: `http://dx.doi.org/doi:10.1007/s10018-016-0172-3`

inputs and radial expansion of all outputs, respectively. Under constant returns to scale, these two approaches will yield the reciprocal efficiency scores. However, in the case of pollution generating production, the conventional Debreu-Farrell measurement based on a proportional increase of all outputs is not an appropriate method for evaluating improvements in production performance when bad outputs are generated simultaneously.

Recognising pollutants as undesirable outputs (by-products) of production process, Färe et al. (1986, 1989) firstly introduced an empirical method covering inefficiency measurements on undesirable outputs, which imposes the property of "weak-disposability", based on Shephard (1970). In these two papers, they advocated that the disposability of emissions should not be free, and that unintended outputs should be disposed off proportionately with the desirable outputs, and that no bad output generated if no intended output produced ("null-jointness").[2] The pollution generating technology modeled to satisfy these properties can be referred as a "weakly disposable technologies" (WD). In many following empirical works, nonparametric or parametric specifications of weak-disposability-based approaches haven been widely employed for measuring the production efficiency, environmental efficiency, and shadow prices of pollution generated.[3]

However, Førsund (2009, 2016) criticized that due to the neglect of material balance principle, a characteristic of inefficiency literature dealing with joint production based on weak-disposability has been that there were hardly any traces of insights from environmental economics on production model formulation. To better explain material balance principle that the mass contained in inputs cannot disappear, but must turn up in desirable outputs and undesirable outputs, Førsund (1972, 1973, 2009) proposed multi-equation production modelling for using the Frisch (1965) multi-equation approach explicitly (assuming efficiency) for the first time within environmental economics. Then, Murty et al. (2012) indicated that the weak-disposability approach, which assumes free disposability of inputs and weakly disposability and null-jointness of desirable and non-desirable outputs might lead to counterintuitive implications for trade-offs between in-

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[2] *See*, e.g. Färe et al. (1996); Tyteca (1997); Färe and Grosskopf (2003).

[3] *See*, e.g. Coggins and Swinton (1996); Färe et al. (1989, 1993, 2005); Grosskopf (1996); Murty and Kumar (2002, 2003).

puts, desirable outputs, and undesirable outputs.[4] In order to resolve the concerns raised in weak-disposability approach, Murty et al. (2012) and Murty and Russell (2016), building on ideas of Frisch (1965), and Førsund (2009) argued analytically that pollution-generating technologies are best modeled as the intersection of two sub-technologies: an intended-production sub-technology and a residual-generation sub-technology. They referred to this structure as a "by-production" (BP) approach to modelling emission-generating technologies. According to this new approach, they distinguished explicitly between emission-causing inputs (like fossil fuels) and non-emission causing inputs (such as capital, labour, etc), such distinction was firstly mentioned in Ayres and Kneese (1969), and decomposed the technology into two separate technology sets (1) a standard *neo-classical (engineering) desirable production technology* which satisfies free disposability with respect to all inputs and desirable outputs and (2) a *nature's emission generating mechanism* that violates free disposability of emissions and emission-causing inputs. BP approach proposes that the latter set should satisfy costly disposability of emissions and emission-causing inputs.

As a fast economic developing country, China's environmental issues have caused significant concerns. Hence, the joint production and environmental efficiency measures computed for different regional locations can provide useful policy guidelines for increasing economic and environmental performances of regions in China. Recently, several studies contributed to relevant literatures about China. Hu and Wang (2006) provided a total-factor energy efficiency measure to analyse the efficiency of China's regional energy usage, but their model only treated energy as one of the multiple inputs and regional GDP as a desirable output without considering any emission as undesirable output. Some recent studies have proposed Data Envelopment Analysis (DEA) models to measure China's regional integrated economic and environmental efficiency, which attempts to decrease the undesirable outputs and increase desirable outputs simultaneously (Bian and Yang, 2010; Wang et al., 2012; Wang, Yu and Zhang, 2013). However, these models are all

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[4] The standard single-equation representation of weak-disposability approach shows the non-positive trade-off between input and undesirable output when desirable output is held fixed and the non-negative trade-off between desirable output and undesirable output with fixed input. These two trade-offs can be argued to be counter to the emission generation fact. *See*, Murty et al. (2012).

based on the "weak-disposability" approach, which assume there exists a proportional relationship between desirable and undesirable outputs. Due to concerns arising from the weak-disposability assumption, the DEA non-parametric efficiency models in this chapter are based on the new BP approach that treats the desirable and undesirable output generation separately and measures each technical efficiency–environmental technical efficiency and technical efficiency in desirable output production, separately.

We employ data from China's 30 province-level regions from 2006 to 2010 to construct the DEA models for measuring the provincial production efficiency and environmental efficiency. In particular, employing the BP approach we measure output-based efficiency indexes in a model where the desirable output is province-level GDP and the undesired outputs are the two main air pollutants, CO_2 and SO_2.

The rest of this chapter is organised as follows: Section 2.2 explains theoretical logic of by-production approach to modelling pollution generating technologies and outlines how to construct the efficiency measures under BP approach. Section 2.3 employs the data to evaluate the regional production and environmental efficiency scores and analyses the relevant reasons for region-level differences seen in the empirical results. Based on the empirical results, some policy implementations are discussed in Section 2.4.

2.2 Methodology

We assume that there are N inputs, M desirable (good outputs), and K emission types (bad outputs). An input vector is denoted by $x = (x_1, ...x_N) \in \mathbb{R}_+^N$, a good output vector is denoted by $y = (y_1, ...y_M) \in \mathbb{R}_+^M$, and a vector of bad outputs is denote by $b = (b_1, ...b_K) \in \mathbb{R}_+^K$.[5] The inputs are indexed by $n = 1, \ldots, N$, the good outputs are indexed by $m = 1, \ldots, M$, and the bad outputs are indexed by $k = 1, \ldots, K$. An

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[5] Here, the authors only consider the bad outputs (emissions) from the production process (e.g. tons of SO_2 and CO_2) and not the externalities they cause.

emission-generating technology is denoted in terms of the output-possibility sets as

$$\begin{aligned} P(x) &= \{(y,b) : x \textit{ can produce } (y,b)\}, \\ T &= \{\langle x,y,b\rangle \in \mathbb{R}_+^{N+M+K} | (y,b) \in P(x)\}, \end{aligned} \tag{2.1}$$

where $P(x)$ is the output-possibility set, which denotes the set of feasible combinations of good and bad outputs that can be produced by input vector x, while T denotes the technology set.

2.2.1 By-production Emission Generating Technologies

An important feature of the BP approach is that it distinguishes between emission-causing and non-emission causing goods. Such distinction was firstly proposed by Ayres and Kneese (1969). Here we can assume that some inputs cause emissions. The N inputs can be classified into non-emission causing and emission-causing inputs. We will assume that the first N_1 inputs are non-emission causing, while the last N_2 inputs are emission-causing. Hence, $N = N_1 + N_2$. The input quantity vector $x = \langle x_1, ..., x_N\rangle \in \mathbb{R}_+^N$ can be partitioned into a vector of non-emission causing inputs, denoted by $x^1 = \langle x_1, ..., x_{N_1}\rangle \in \mathbb{R}_+^{N_1}$ and a vector of emission-causing inputs, denoted by $x^2 = \langle x_{N_1+1}, ..., x_N\rangle \in \mathbb{R}_+^{N_2}$. Hence, $x = \langle x^1, x^2\rangle \in \mathbb{R}_+^N$.

Parametric Representation of BP Technologies

Under the BP approach, when producers use pollution causing inputs, the production of desirable output would set a nature's residual mechanism in motion, which will lead to the generation of undesirable outputs (Murty et al., 2012). Therefore, the emission-generating technologies can be split two technology sets: T_1 is the conventional technology set, which reflects the transformation of all inputs into desirable outputs; and T_2 denotes nature's residual generating technology, which shows how emission-causing goods used in T_1 generate emissions in nature.[6] Hence, the parametric formulation of a BP emission

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[6] The model can be extended to include abatement activities as in Murty et al. (2012) and Murty (2015b).

generating technologies is given as

$$\begin{aligned} T_{BP} &= T_1 \cap T_2, \quad \text{where} \\ T_1 &= \{\langle x^1, x^2, y, b\rangle \in \mathbb{R}_+^{N+M+K} | f(x^1, x^2, y) \leq 0\}, \\ T_2 &= \{\langle x^1, x^2, y, b\rangle \in \mathbb{R}_+^{N+M+K} | g(x^2, b) \geq 0\}. \end{aligned} \tag{2.2}$$

Functions $f : \mathbb{R}_+^{N+M+K} \longrightarrow \mathbb{R}$ and $g : \mathbb{R}_+^{N+M+K} \longrightarrow \mathbb{R}$ are the parametric representations of sets T_1 and T_2, respectively. We assume that both functions are continuously differential and the properties we will impose on functions f and g below will ensure that T_{BP} is non-empty.

We would like the function f to represent the conventional neo-classical technology set T_1. Hence, we will assume the following signs for the derivatives of function f:

$$\begin{aligned} f_{x_n}(x^1, x^2, y) &\leq 0, \quad \forall\, n = 1, \ldots, N_1, \\ f_{x_n}(x^1, x^2, y) &\leq 0, \quad \forall\, n = N_1 + 1, \ldots, N, \\ f_{y_m}(x^1, x^2, y) &\geq 0. \quad \forall\, m = 1, \ldots, M \end{aligned} \tag{2.3}$$

The signs of these derivatives imply that all inputs satisfy standard free disposability and all desirable outputs are also freely disposable. In particular, along the frontier of technology T_1, there is a positive relationship between any input and any desirable output. Note also that the technology set T_1 is independent of the level of emissions. Emissions do not affect intended output production.[7]

Set T_2 in (2.2) reflects the physical and chemical mechanism of pollution generation in nature. In nature, the more are the emission-causing goods are used the more are the emissions generated. The function g should capture this. We assume the following signs for the derivatives of function g.

$$\begin{aligned} g_{x_n}(x^2, b) &\leq 0, \quad \forall\, n = N_1 + 1, \ldots, N, \\ g_{b_k}(x^2, b) &\geq 0. \quad \forall\, b_k = 1, \ldots, K. \end{aligned} \tag{2.4}$$

Under these sign conventions, the production vectors $\langle x^1, x^2, y, b\rangle \in \mathbb{R}_+^{N+M+K}$ that satisfy

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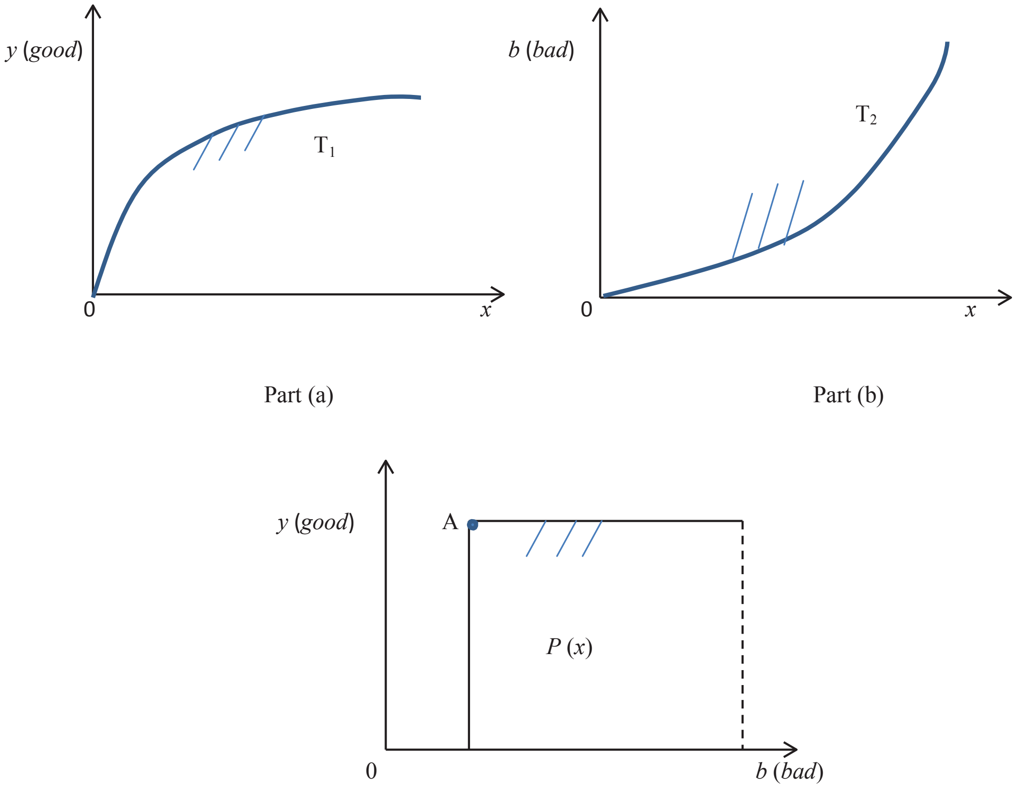
[7] Murty (2015b) provides a generalisation of this where emissions from a firm may affect its own intended production in a beneficial or detrimental manner.

$g(x^2, b) = 0$ form the lower frontier of technology T_2. For every vector of emission-causing inputs, this frontier gives the minimal levels of emissions generated in nature. This property has been called costly disposability of emissions in Murty et al. (2012). This captures our intuition that emissions are not freely disposable as outputs. Usage of emission-causing inputs definitely produces some minimal emissions. Employing the implicit function theorem, it can be shown that these sign conventions imply that the trade-off between any emission-causing input and any emission type along the lower frontier of technology T_2 is $-\frac{g_{b_k}}{g_{x_n}}$, which is non-negative, provided $g_{x_n} \neq 0$ for $n = N_1 + 1, \ldots, N$. Thus, this captures the positive relation between emission-causing goods such as fossil fuels and emissions such as SO_2.



Part (a)

Part (b)

Part (c)

Figure 2.1: By-production Pollution Generating Technologies

In Figure 2.1, we assume $M = N = K = 1$ and $N_1 = 0$ (that is the single input is emission-causing). For every level of the input, parts (a) and part (b) in Figure 2.1 illustrate the maximal level of the desirable output produced in T_1 and minimal level of undesirable outputs generated in T_2, respectively. Part (c) reflects the output possibility set under BP approach. This shows that given input level x, there is only one combination of the good and the and the bad output that is efficient, namely, the point A. A indicates the maximal amount of the good output and the minimal amount of the bad output that input level x can produce under T_1 and T_2, respectively.

Non-parametric Representation of BP Technologies

Murty et al. (2012) employ a non-parametric formulation of their BP technology for measuring technical efficiency. The notation that we will employ for a DEA construction of the non-parametric version of the BP technology is as follows: Let the matrix of observations on non-pollution causing inputs be denoted by $X^1_{D\times N_1}$ and the pollution causing inputs be denoted by $X^2_{D\times N_2}$. Let the matrices of observations on desirable and undesirable outputs be denoted as before by $Y_{D\times M}$ and $B_{D\times K}$, respectively. Then the standard DEA non-parametric representation of BP can be specified as

$$\begin{aligned} T_1 &= \left\{\langle x, y, b\rangle \in \mathbb{R}^{N+M+K}_{+} | \lambda[X^1, X^2] \leq \langle x^1, x^2\rangle \wedge \lambda Y \geq y, \quad \lambda \in \mathbb{R}^D_+\right\}, \\ T_2 &= \left\{\langle x^1, x^2, y, b\rangle \in \mathbb{R}^{N+M+K}_{+} | \mu X^2 \geq x^2 \wedge \mu B \leq b, \quad \lambda \in \mathbb{R}^D_+\right\}. \qquad (2.5) \end{aligned}$$

The overall BP technology is the intersection of T_1 and T_2. Hence, it is derived under DEA as

$$\begin{aligned} T_{BP} = T_1 \cap T_2 \;&=\; \Big\{\langle x^1, x^2, y, b\rangle \in \mathbb{R}^{N+M+K}_{+} | \lambda[X^1, X^2] \leq \langle x^1, x^2\rangle \\ &\wedge \quad \lambda Y \geq y \wedge \mu X^2 \geq x^2 \wedge \mu B \leq b, \langle \lambda, \mu\rangle \in \mathbb{R}^{2D}_{+}\Big\}. \qquad (2.6) \end{aligned}$$

Here, $\lambda \in \mathbb{R}^D_+$ and $\mu \in \mathbb{R}^D_+$ here represent the intensity vectors, which are the weights assigned to each observation (DMU) to construct the technically efficient frontiers of T_1 and T_2 under DEA.

2.2.2 Production and Environmental Efficiency measurements under BP Approach

In this section, we will employ non-parametric approached to measure technical efficiency under the BP approach. Since BP approach distinguishes between intended production technology T_1 and nature's emission-generating technology T_2, a technical efficiency index defined under the BP approach can be implicitly or explicitly decomposed into two components: index of good-output (production) efficiency and an index of bad output (environmental) efficiency.

In particular, we will focus on output-based measures of efficiency and consider two types of efficiency indexes: the hyperbolic (HYP) efficiency index and the modified Färe-Grosskopf-Lovell (FGL) efficiency index to construct the productive efficiency and environmental efficiency measurements under BP technology.[8] By using DEA technologies approach, these technical indexes could be generated. Meanwhile, through comparing two efficiency scores in HYP, we could also find each DMU are either weakly productive efficient or environmentally efficient under the BP emission generating technology. In addition, the FGL index will be modified to suit for the BP approach application, which can illustrate the integrated efficiency of each DMU by both considering intended outputs production and unintended outputs generation. After discussing structures of efficiency measurement under the BP approach, the comparative arguments will also be confirmed by employing specific data set in next section.

2.2.3 HYP Measurement under BP Approach

The HYP measure of efficiency decomposes efficiency explicitly into desirable production efficiency, which is defined relative to set T_1, and environmental efficiency, which is defined relative to T_2. The former is denoted by $D_{HYP(1)}$ and the latter is denoted by $D_{HYP(2)}$. Intuitively, holding all inputs fixed, $\frac{1}{D_{HYP(1)}}$ measures the maximal factor by

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[8] These two efficiency measures indexes have been widely used in study WD technology. In this section, we adapt these measures and employ them to measure technical efficiency under the BP approach.

which the given desirable output vector can be scaled-up and yet be technologically feasible, while $\frac{1}{D_{HYP(2)}}$ captures the maximal factor by which the bad output vector can be scaled-down and yet be technologically feasible. The overall index of efficiency, denoted by D_{HYP} is obtained by taking the maximum of $D_{HYP(1)}$ and $D_{HYP(2)}$. This implies that $\frac{1}{D_{HYP}}$ is the maximal extent to which the good output vector and the bad output vector can be simultaneously scaled-up and scaled-down, respectively, and yet be technologically feasible.

The mathematical programme to measure hyperbolic efficiency under the BP approach is:

$$\begin{aligned}
&D_{HYP}(x,y,b;T_{BP})\\
&= \inf_{\beta>0}\{\beta|\langle x,y/\beta,b\beta\rangle \in T_{BP}\}\\
&= \inf_{\beta>0}\{\beta|\langle x,y/\beta,b\beta\rangle \in T_1 \wedge \langle x,y/\beta,b\beta\rangle \in T_2\}\\
&= \max\{\beta_1,\beta_2\}.\\
D_{HYP(1)} &= \inf_{\beta_1>0}\{\beta|\langle x,y/\beta_1,b\rangle \in T_1\}\\
D_{HYP(2)} &= \inf_{\beta_2>0}\{\beta|\langle x,y,b\beta_2\rangle \in T_2\}
\end{aligned} \tag{2.7}$$

Where, the last two equalities follow from the fact that, in the BP approach, given a vector of inputs, the output possibility sets corresponding to T_1 and T_2 are independent. When $D_{HYP(1)} = 1$, the observed point is on the weakly efficient frontier of T_1 and when $D_{HYP(2)} = 1$, the observed point is on the weakly efficient lower frontier of T_2. An observation is inefficient when D_{HYP} is strictly less than one. There might be an observation, for which D_{HYP} equals to one, while $D_{HYP(1)}$ and $D_{HYP(2)}$ might not both equal to one. This implies that the hyperbolic measure will judge this observation as efficient, even when it is inefficient in desirable output production or undesirable output production.

Below, we present the DEA programme for measuring hyperbolic efficiency: For each

DMU d' in each different year t, HYP efficiency is measured as

$$\begin{aligned}
D_{HYP}\left(x_{d'}^t, y_{d'}^t, b_{d'}^t; T_{BP}\right) &= \max\left\{\beta_1, \beta_2\right\}, \\
D_{HYP(1)} &= \min_{\lambda,\beta_1} \beta_1 \\
s.t. \sum_{t=1}^{T}\sum_{d=1}^{D} \lambda_d^t y_{d,m}^t &\geq y_{d',m}^t/\beta_1, \forall m = 1, ..., M \\
\sum_{t=1}^{T}\sum_{d=1}^{D} \lambda_d^t x_{d,n}^t &\leq x_{d',n}^t, \forall n = 1...N \\
\lambda_d^t &\geq 0 \quad \forall\, d = 1, \ldots, D.
\end{aligned}$$

$$\begin{aligned}
D_{HYP(2)} &= \min_{\mu,\beta_2} \beta_2 \\
s.t. \sum_{t=1}^{T}\sum_{d=1}^{D} \mu_d^t b_{d,k}^t &\leq b_{d',k}^t \beta_2, \forall k = 1, ..., K \\
\sum_{t=1}^{T}\sum_{d=1}^{D} \mu_d^t x_{d,n}^t &\geq x_{d',n}^t, \forall n = N_1 + 1, ..., N \\
\mu_d^t &\geq 0 \quad \forall\, d = 1, \ldots, D. \qquad (2.8)
\end{aligned}$$

2.2.4 Modified FGL Measurement under BP Approach

Murty et al. (2012) consider the output-based version of the FGL approach to construct a modified FGL efficiency index with respect to the BP approach. This index is based on the coordinate-wise expansions of desirable outputs and coordinate-wise contractions of undesirable outputs.[9] The FGL index decomposes under the BP approach into production and environmental efficiency measures as follows:[10]

$$\begin{aligned}
& D_{FGL}(x, y, b; T_{BP}) \\
&=: \frac{1}{2}\min_{\theta,\gamma}\{\frac{\sum_m \theta_m}{M} + \frac{\sum_k \gamma_k}{K} | \langle x, y \oslash \theta, b \otimes \gamma\rangle \in T_{BP}\} \\
&= \frac{1}{2}\min_{\theta}\{\frac{\sum_m \theta_m}{M} | \langle x, y \oslash \theta, b\rangle \in T_1\} \qquad (2.9) \\
&+ \frac{1}{2}\min_{\gamma}\{\frac{\sum_k \gamma_k}{K} | \langle x, y, b \otimes \gamma \in T_2\rangle\} \\
&= \frac{1}{2}[D_{FGL(1)}(x, y, b; T_1) + D_{FGL(2)}(x, y, b; T_2)].
\end{aligned}$$

---

[9] The output-oriented version index takes up all slack in output spaces and leaves the slack in inputs spaces.

[10] We denote $y \oslash \theta = \langle y_1/\theta_1, ...y_M/\theta_M\rangle$ and $b \otimes \gamma = \langle b_1\gamma_1, ...b_K\gamma_K\rangle$.

Here, $D_{FGL(1)}$ measures the production efficiency of the DMU in desirable production, while $D_{FGL(2)}$ measures its environmental efficiency. The FGL efficiency index takes a simple average of the production efficiency and environmental efficiency to compute the overall efficiency of DMUs. The key feature of this index is that a DMU is judged as efficient if and only if it is efficient in both desirable outputs and environmental directions, *i.e.,* if and only if $D_{FGL(1)} = D_{FGL(2)} = 1$. Compare this with the hyperbolic measure of efficiency, where a DMU can be judged efficient even when it is not efficient in the direction of desirable outputs or in the environmental direction.

The DEA algorithm for computing FGL index is given as follows. To compute efficiency of each DMU d' in each year t, we solve the following optimisation problem:

$$\begin{aligned}
D_{FGL}(x_d^t, y_d^t, b_d^t;\ T_{BP}) &= \min_{\lambda,\theta,\mu,\gamma} \frac{1}{2}\left[\frac{\sum_{m=1}^{M}\theta_m}{M} + \frac{\sum_{k=1}^{K}\gamma_k}{K}\right] \\
s.t. \sum_{t=1}^{T}\sum_{d=1}^{D}\lambda_d^t y_{d,m}^t &\geq y_{d',m}^t/\theta_m \quad \forall m = 1,...M \\
\sum_{t=1}^{T}\sum_{d=1}^{D}\lambda_d^t x_{d,n}^t &\leq x_{d',n}^t \quad \forall n = 1,...N \\
\sum_{t=1}^{T}\sum_{d=1}^{D}\mu_d^t b_{d,k}^t &\leq b_{d',k}^t\gamma_k \quad \forall k = 1,...K \\
\sum_{t=1}^{T}\sum_{d=1}^{D}\mu_d^t x_{d,n}^t &\geq x_{d',n}^t \quad \forall n = N_1 + 1,...N \\
\lambda_d^t \geq 0,\ \mu_d^t &\geq 0, \quad \forall\, d = 1,\ldots,D
\end{aligned} \tag{2.10}$$

Since the T_1 and T_2 are independent from each other, D_{FGL} could be calculated separately as following:

$$\begin{aligned}
D_{FGL(1)} &= \min_{\lambda,\theta}\frac{\sum_{m=1}^{M}\theta_m}{M} \\
s.t. \sum_{t=1}^{T}\sum_{d=1}^{D}\lambda_d^t y_{d,m}^t &\geq y_{d',m}^t/\theta_m \quad \forall m = 1,...M \\
\sum_{t=1}^{T}\sum_{d=1}^{D}\lambda_d^t x_{d,n}^t &\leq x_{d',n}^t \quad \forall n = 1,...N \\
\lambda_d^t &\geq 0, \quad \forall\, d = 1,\ldots,D
\end{aligned} \tag{2.11}$$

$$
\begin{aligned}
D_{FGL(2)} &= \min_{\mu,\gamma} \frac{\sum_{k=1}^{K} \gamma_k}{K} \\
\sum_{t=1}^{T}\sum_{d=1}^{D} \mu_d^t b_{d,k}^t &\leq b_{d',k}^t \gamma_k \quad \forall k = 1, ...K \\
\sum_{t=1}^{T}\sum_{d=1}^{D} \mu_d^t x_{d,n}^t &\geq x_{d',n}^t \quad \forall n = N_1 + 1, ...N \\
\mu_d^t &\geq 0, \quad \forall\, d = 1, \ldots, D
\end{aligned}
\tag{2.12}
$$

When the equal weights are given to measurements in T_1 and T_2, the coordinate-wise FGL efficiency index could be calculated as $\frac{1}{2}(D_{FGL(1)} + D_{FGL(2)})$.

2.3 Empirical Analysis

In this section, the empirical analysis will be carried out using China's province-level data. The HYP and modified FGL indexes under BP approach to modelling pollution generating technologies will be implemented to measure the intended production and environmental efficiency for different provincial regions. We will analyse our results in the context of current Chinese environmental protection regulation reviews and provide some explanations for our empirical results.

2.3.1 Data

In this study, we consider 30 Chinese provincial administrative divisions as DMUs from 2006 to 2010.[11] We also divide these 30 regions into four major parts: eastcoast, central, northeast and west areas from the perspective of China's economic development. The details are shown in Figure 2.2.

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[11] Due to the lack of some data on regions such Tibet, Hongkong, Macau and Taiwan, we only consider 30 provincial level regions, which are 22 provinces, 4 municipalities and 4 autonomous regions.

Parts	Province-level regions
Eastcoast	Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan
Central	Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan
Northeast	Liaoning, Jilin, Heilongjiang
West	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

Figure 2.2: Map of China's Four Economic Parts

The annual GDP for each province is considered as one desirable output (y). The data on labour and capital stock are selected as the non-polluting cause inputs (x^1). In order to eliminate the inflation effect, GDP data is deflated to the price of 2000 and measured in hundreds of million CNY.[12] The GDP and labour data was obtained from the "China Statistical Yearbook". However, the capital stock could not be gathered directly from the official released data resources. In this chapter, we adopt the Perpetual Inventory Method (PIM) to estimate the annual capital stocks for each province from 2006 to 2010.[13]

The annual total amounts of coal, oil and natural gas consumed by each region are selected for polluting cause inputs (x^2). The information of three energy inputs is from the "China

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[12] CNY is an abbreviation for Chinese currency "*Yuan*".

[13] The PIM could be given as

$$K_{i,t} = K_{i,t-1}\left(1-\delta_i\right) + I_{i,t}.$$

Where, i and t represent the i^{th} province and t^{th} year, respectively. K denotes the capital stock. δ and I denote the depreciation rate and capital asset investment of year, respectively. The initial capital stock (based year: 2000) and depreciation rates are derived from Zhang et al. (2004). The annual capital asset investment is obtained from the "China Statistical Yearbook".

Energy Statistical Yearbook". The annual net volume of sulfur dioxide (SO_2) and gross volume of carbon dioxide (CO_2) are two undesirable outputs (b). The data on SO_2 was obtained from the "China Environment Yearbook".[14] However, the data on CO_2 could not be obtained directly. In this chapter, we calculate the gross volume of CO_2 emission from the algorithm based on the fossil fuels combustion, which is provided by the IPCC (2006).[15] The descriptive statistics of all variables computed from 2006 to 2010 are shown in Table 2.1.

Table 2.1: Summary Statistics of Inputs and Outputs Variables

Variables*	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
2006-2010					
GDP	150	8377.93	6872.66	504.85	32316.06
SO_2	150	67.32	39.54	2.1	168.7
CO_2	150	34455.17	23683.17	2694.3	117985.5
Capital	150	27875.75	21546.87	2394.62	108537.9
Labour	150	404.20	233.39	42.92	1086.77
Coal	150	11250.85	8390.2	332.22	37327.89
Oil	150	735.88	514.09	76.92	2754.68
Gas	150	28.21	27.81	0.48	175.26

* Unit of GDP and capital stock is 100 million CNY. Unit of labour is 10000 person. Unit of SO_2 and CO_2 is 10000 ton. Unit of coal, oil and gas are 10000 ton, 10000 ton and 100 million cu.m, respectively.

2.3.2 Efficiency Results Analysis

In this study, we employ the non-parametric techniques (DEA method) to compute the efficiencies of DMUs under BP emission-generating technologies. The main feature of BP is that the total pollution generating technologies can be decomposed as two parts: a standard intended production technology (T_1) and a nature's emission generating mecha-

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[14] The definition of SO_2 variable can be found in the National Bureau of Statistics of China. Net SO_2 emission refers to volume of sulphur dioxide emission from burning fossil-fuel during production in the premises of enterprises in each region for a given period of time.

[15] The reference approach to calculate the CO_2 emission is designed as

$$CO_{2emission} = \sum_i (AC_i \cdot CF_i \cdot CC_i) \cdot COF \cdot 44/12.$$

Here, AC_i represents the apparent energy consumption for fossil fuel i . CF_i is the conversion factor for fuel i to energy. CC_i is the carbon content for i fuel. COF is the carbon oxidation factor, usually the value is 1. And $44/12$ equals to molecular weight ratio of CO_2 to C. The data on energy consumption are taken from the "China Energy Statistical Yearbook".

nism (T_2). Then for each DMU, both efficiency measurement (e.g. HYP and FGL) under BP would get two results corresponding to the efficiency level of T_1 and T_2, and one integral technical efficiency score for overall joint production technology. The HYP and FGL under BP technologies are shown from Table 2.7 to Table 2.12. The descriptive statistics of all efficiency results are shown in Table 2.2.

Table 2.2: Summary Statistics of Calculated HYP and FGL Efficiencies under BP

Efficiency Indexes	**Obs.**	**Mean**	**Median**	**Std. Dev.**	**Min**	**Max**
2006-2010						
$D_{HYP(1)}$	150	0.8420	0.9222	0.1730	0.4157	1.0000
$D_{HYP(2)}$	150	0.9065	0.9327	0.1013	0.5258	1.0000
D_{HYP}	150	0.9546	0.9984	0.0703	0.6800	1.0000
$D_{FGL(1)}$	150	0.8420	0.9222	0.1730	0.4157	1.0000
$D_{FGL(2)}$	150	0.8005	0.8004	0.1175	0.5233	1.0000
D_{FGL}	150	0.8212	0.8413	0.1097	0.5629	1.0000

As discussed in the theoretical section, given the fixed levels of inputs, the output-oriental HYP is defined by the intended output expansions and unintended output contractions by a maximum single scalar, and the FGL is defined by the coordinate-wise expansion of all desirable outputs and contractions of all undesirable outputs. Therefore, the overall integrated FGL results for each DMU would be less or equal to the HYP results, which means the HYP efficiency measurement might overestimate the technical efficiency level for each DUM. This can also be observed and proved in Figure 2.3. Hence, we recommend employing a coordinate-wise FGL under BP approach (BP-FGL) to measure the production and environmental efficiency levels for each DUM.[16]

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[16] Due to the only one intended output is chosen (*e.g.*, $M = 1$) in this work, the results of decomposition of production efficiency in FGL ($D_{FGL(1)}$) for each region in every year are exactly same with production efficiency in HYP ($D_{HYP(1)}$). If $M \geq 2$, the programming for production efficiency calculation should be designed to take the average (coordinate-wise) distances from each desirable output observation to the corresponding possibility frontier, based on 2.10. Here, $D_{HYP(1)} = D_{FGL(1)}$ is the occasional case with $M = 1$.

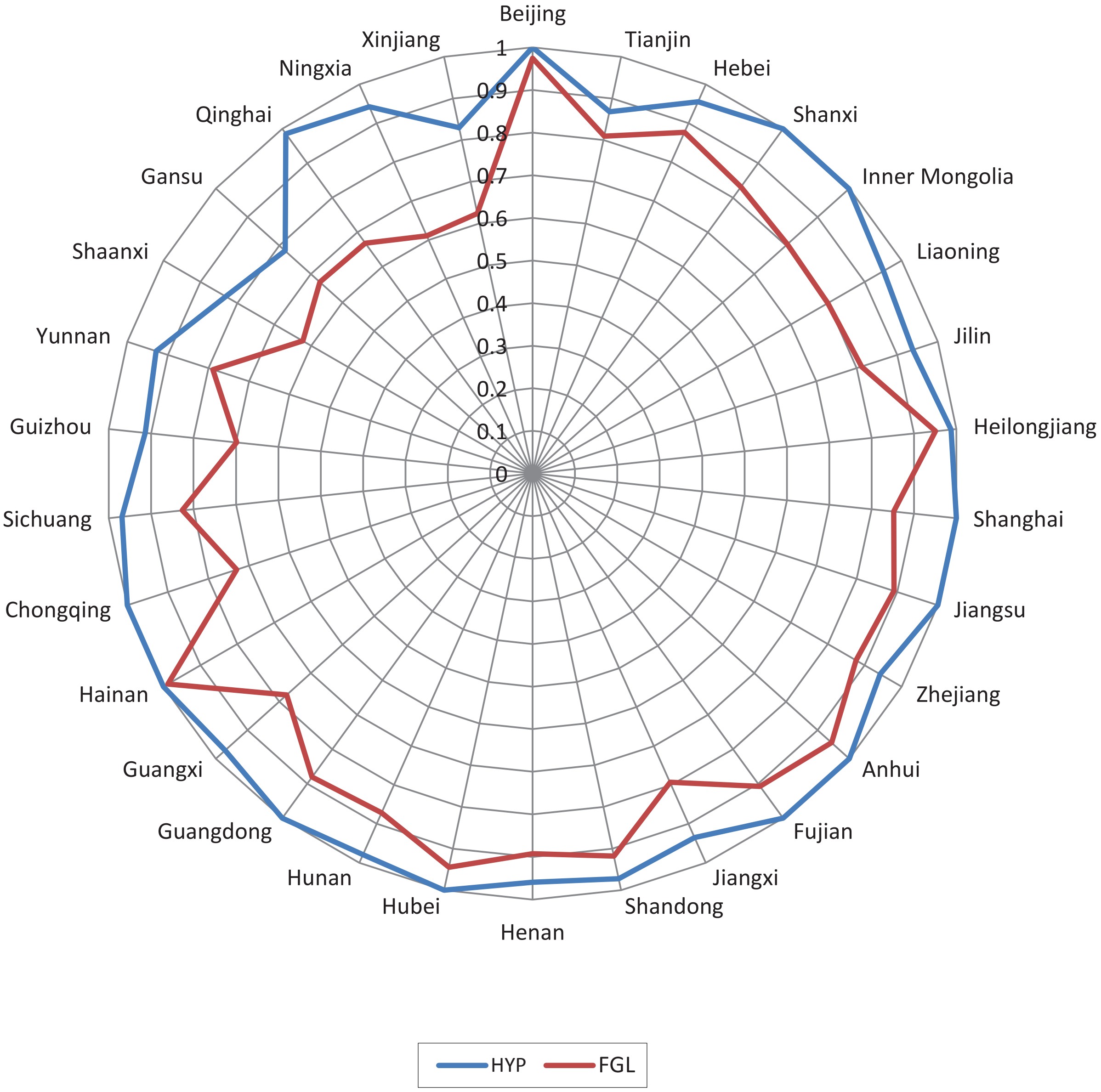

Figure 2.3: The Five-year Average Integrated HYP vs FGL Efficiency under BP

According to the four-part areas classification, the average BP-FGL efficiency results for each economic area are shown in Table 2.3 and Figure 2.4. We can observe that in terms of production efficiency, the eastcoast area gets the highest efficiency level, the central and northeast areas rank in the second and third high position, respectively. They were all above the average nation efficiency level during this five year period. However, the production efficiency level of the west area is lowest, which is also the only one region lower than the national level during the five-year study period. On the other hand, the environmental efficiency measurement shows differently. In 2006, the eastcoast was the highest,

Table 2.3: Average Regional BP-FGL Efficiency Results in Four Parts

	2006	**2007**	**2008**	**2009**	**2010**	**Averge**
$D_{FGL(1)}$						
Eastcoast area	0.9436	0.9583	0.9723	0.9740	0.9774	0.9651
Central area	0.9188	0.9311	0.9202	0.9178	0.9203	0.9216
Northeast area	0.8822	0.8684	0.8600	0.8731	0.8662	0.8700
West area	0.6766	0.6711	0.6651	0.6827	0.6998	0.6790
Whole selected area	0.8346	0.8385	0.8380	0.8458	0.8531	0.8420
$D_{FGL(2)}$						
Eastcoast area	0.8081	0.8187	0.8268	0.8548	0.8419	0.8300
Central area	0.8029	0.8200	0.8291	0.8566	0.8795	0.8376
Northeast area	0.8011	0.7909	0.8433	0.8673	0.8881	0.8381
West area	0.7038	0.7406	0.7323	0.7605	0.7778	0.7430
Whole selected area	0.7681	0.7875	0.7943	0.8218	0.8306	0.8005
D_{FGL}						
Eastcoast area	0.8758	0.8885	0.8995	0.9144	0.8937	0.8944
Central area	0.8608	0.8756	0.8747	0.8872	0.8999	0.8796
Northeast area	0.8416	0.8296	0.8516	0.8702	0.8771	0.8541
West area	0.6902	0.7058	0.6987	0.7216	0.7389	0.7110
Whole selected area	0.8014	0.8130	0.8161	0.8338	0.8418	0.8212

but from 2007 to 2010, it was exceeded by the central area. Moreover, the central area was exceeded by the northeast after 2008. Only the west area had a relatively poor performance and this was even below the national levels during these five years. In terms of integrated efficiency, the eastcoast area had the highest overall technical efficiency level, followed by the central and northeast areas, and the west area was the lowest. Similarly, only the west area was lower than the national average level; the other three are all higher than the nation average efficiency level.

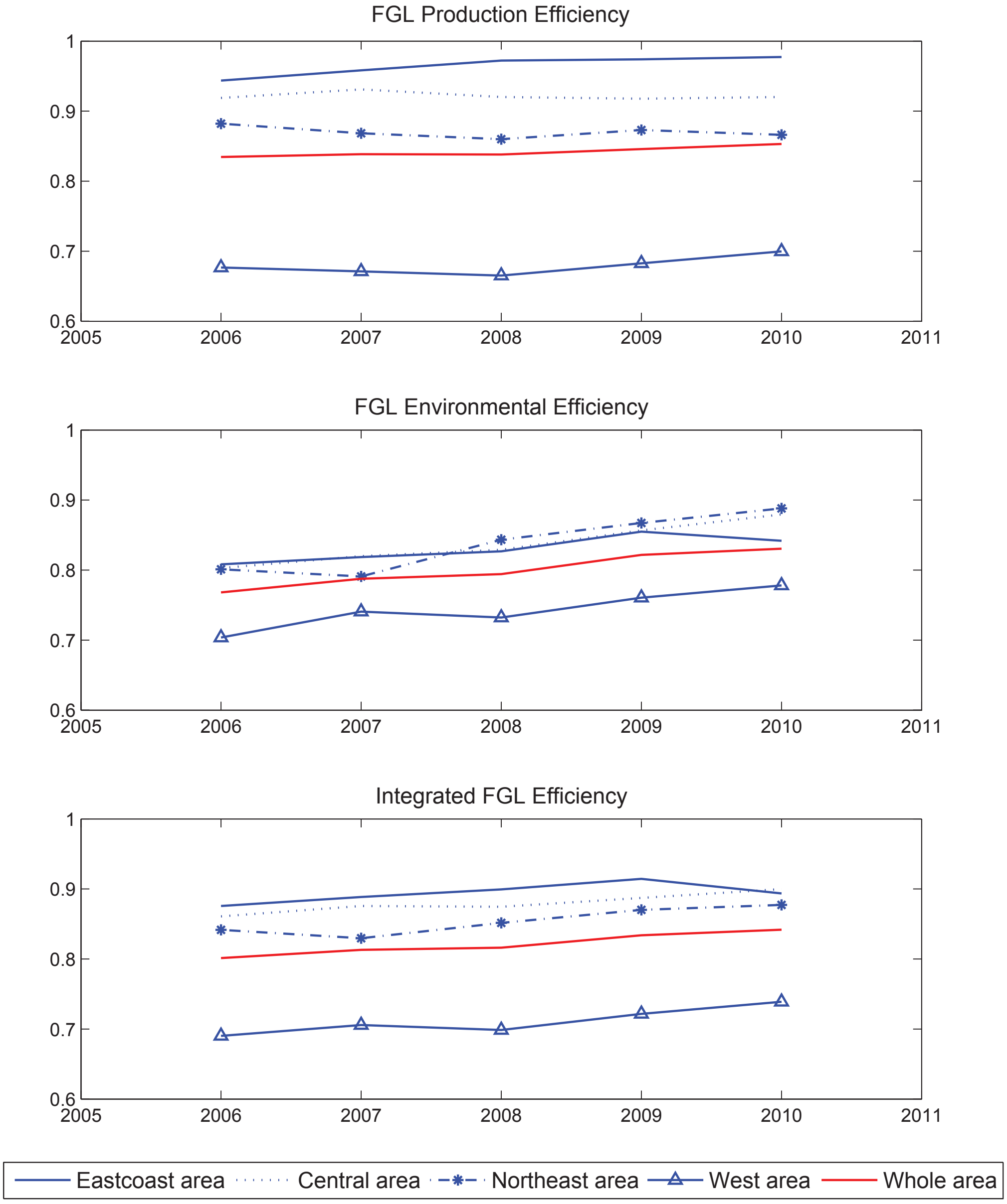

Figure 2.4: Regional Average BP-FGL Efficiency Measurements from 2006 to 2010

When we target each province's efficiency results of four parts in 2010 (Figure 2.5), we found that production efficiency scores for all provinces in the eastcoast were always higher than the environmental efficiency levels. For the central area, most of the provinces also had similar characteristics to the eastcoast, except Shanxi, which had the higher environmental efficiency than production efficiency. In the northeast, Liaoning was the only province which had the higher a production efficiency compared to environmental efficiency. But in west, only Gunaxi, Sichuan and Gansu three provinces had higher production efficiency levels than environmental efficiency levels; the other provinces all had higher scores in environmental efficiency than production efficiency. Even though the most west provinces achieved weak environmental efficiency, the overall environmental efficiency level was still lower than the other three regions and below the national average level.

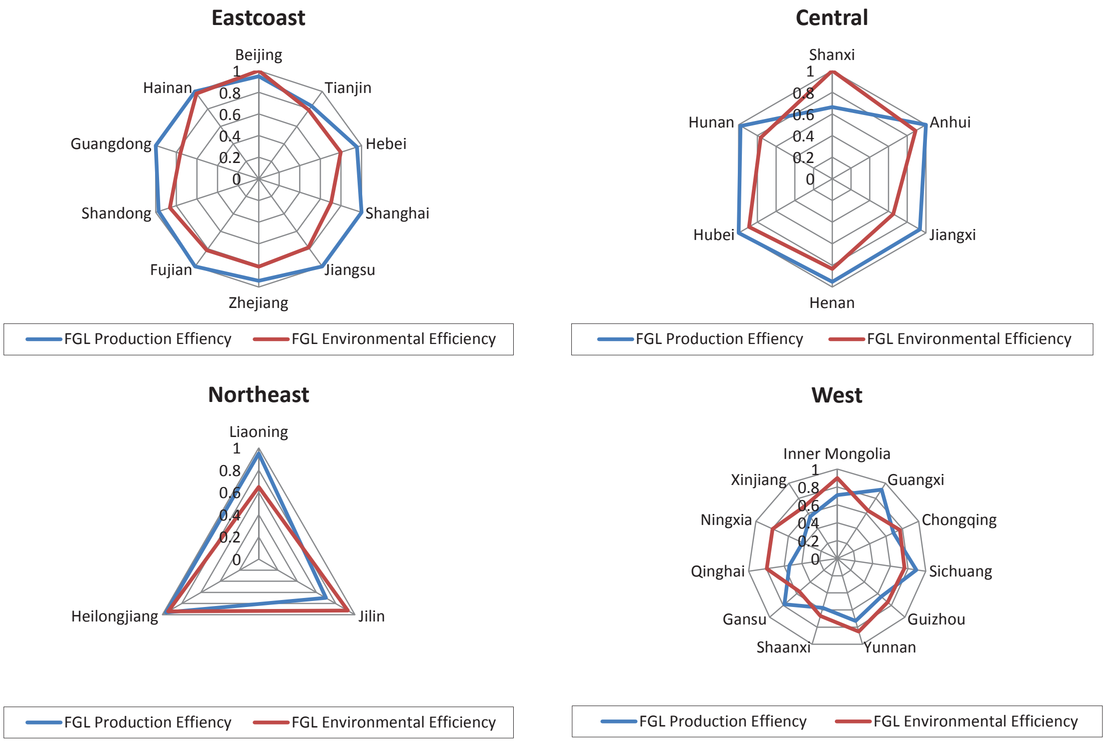

Figure 2.5: Five-year Average BP-FGL Production and Environmental Efficiency Scores

Therefore, it could be concluded that for most provinces in the eastcoast and central areas, the production efficiency level was higher than the environmental efficiency level, and in northeast and west, the most provinces achieved more environmental efficiency than production efficiency measures. Furthermore, from the view of the whole country, there were significant gaps in the overall production efficiency levels across all different regions, but in environmental efficiency measurements, the gaps of efficiency levels among the four regions were not such obvious as which in production efficiency measures. Lastly, we also found that the west area was always the lowest in terms of production and environmental measurements.

2.3.3 Reason Discussion

As discussed above, China's regional development disparity is partially reflected in our BP-FGL results. Eastcoast area always exhibited a strong advantage in production efficiency. The results of west area revealed the worst performance in both production and environmental efficiency measurement. From the comprehensive technical efficiency respective, it can be concluded that the eastcoast was the best, followed by central and northeast areas, and the west had the worst results. The gaps of efficiency levels between the west compared with the other three regions are all significant.

The imbalance in regional development in China has been pointed out in many studies. Hu and Wang (2006) firstly used total-factor energy efficiency index to measure China's regional efficiency of energy input utilisation, and found there are varied technology levels among the different areas, with the east having the highest and west and central areas being the worst. Lu and Lo (2007) used a cross-efficiency measure to assess the overall technical efficiency in 31 provinces in China and found that the coastal regions performed on average better than the inland regions for both economic and environmental considerations. Therefore, our empirical results about production efficiency measurement correctly characterize this regional disparity issue in China and are in correspondence with relevant studies. Some reasons for these regional gaps in production efficiency measurements could be summarized as different regional industrial structures, unequal economic development stages, and government reform policies implemented with preference for the eastcoast area, for example (Fleisher and Chen, 1997; Kanbur and Zhang, 1999, 2005).

Due to the BP approach separating the pollution-generating technologies into two independent parts, our production and environmental efficiency measurements can be conducted to capture each DMU's efficiency based on the two technology parts, respectively. Therefore, from the theoretical view, each province's production technology would not directly influence its environmental efficiency level. The environmental efficiency mainly depends on the different levels of emission generation, given the fixed amounts of fossil fuels usage and pollution reductions. Furthermore, different types of energy resources utilisation and the effectiveness of abatement activities for each province or region should be reflected in our environmental efficiency measurement results. Table 2.4 also verifies that production efficiency ($D_{HYP(1)}$ or $D_{FGL(1)}$) is not correlated with environmental efficiency ($D_{HYP(2)}$ or $D_{FGL(2)}$).

Table 2.4: Spearman's Correlation Tests on Five-year Average HYP and FGL Efficiency Indexes under BP Appraoch

	$D_{HYP(1)}$	$D_{HYP(2)}$	D_{HYP}	$D_{FGL(1)}$	$D_{FGL(2)}$	D_{FGL}
$D_{HYP(1)}$	1.0000					
$D_{HYP(2)}$	-0.0500	1.0000				
D_{HYP}	0.5903**	0.5975**	1.0000			
$D_{FGL(1)}$	1.0000**	-0.0500	0.5903**	1.0000		
$D_{FGL(2)}$	0.1782	0.6010**	0.4788**	0.1782	1.0000	
D_{FGL}	0.8261**	0.2851	0.6483**	0.8261**	0.6350**	1.0000

* Significant at 10%.
** Significant at 5%.

Therefore, through analysing the underlying reasons for the various environmental efficiency levels in different regions, this study can make recommendations on the appropriate environmental policy adjustments for the Chinese government to improve the regional environmental efficiency levels without harming their production efficiency.

In terms of fossil fuels usage, much research has indicate that coal consumption has always occupied the highest percentage of China's energy usage structure. From the 1980s to 2014, coal accounted for around 70% of the production and consumption of Chinese domestic primary energy sources.[17] This heavy reliance on coal usage in China has led to serious environmental problems. In 2012, China's 79% total SO_2 emission stems from the direct combustion of coal.[18] Similarly, CO_2 produced by coal consumption in long term CO_2 emissions generated from energy activities remains about 80% (IEA, 2013). Therefore, various qualities of coal utilisation in different areas may partially lead to the different degrees of emission and environmental efficiency levels. Wang and Li (2001) state that in China, the sulphur content of power coal varies with different regions rang-

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[17] Source from: China National Energy Administration

[18] Statistical data come from the report of "Coal use contribution to China's air pollution" by China's coal consumption control scheme and policy research, 2014.

ing from 0.14% to 5.3%. From the sampling and analysing, they also point out that the sulphur content of coal conserves in the northeast is the lowest, on average 0.45%. The sulphur content in Beijing, Jilin, Yunnan etc. is on average 0.5%. However, the highest sulphur coals (average of 2.79%, with individual regions as high as 5.0%) are mainly observed in the southwest area, like Sichuan Guangxi and Guizhou. Similar results are also found in other literature (Hong et al., 1993; Xiao and Liu, 2011). Due to the different types of coal exploitation and use between the east and west areas, the emission levels from fossil fuel combustion will be influenced. This characteristic can also be reflected in and is consistent with our regional environmental efficiency measurements.

Table 2.5: Descriptive Statistics of Data for Reason Discussion

Variables	**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
2006-2010					
$D_{FGL(2)}$	150	0.8004	0.1175	0.5233	1.0000
X_1	150	0.4792	0.1997	0	0.8267
X_2	150	1.4632	0.7329	0.582	4.099
X_3	150	1.2333	0.5341	0.46	3.76
X_4	150	0.0871	0.0911	0.0044	0.6954
X_5	150	1.6543	1.0219	0.2812	6.3440

* Unit of energy intensity (X_2) is tce/10000 CNY, abbreviation of tons of coal equivalent per 10000 CNY. The other units are expressed as percentage.

In reality, even though the influences on the atmospheric environment from coal resource distribution and consumption structure in different areas are inevitable, the strict regulations or policies for controlling low quality coal use and setting up emission standards can also play important roles in forcing the producers to reduce the pollution-causing inputs use and make more efforts in abatement activities in order to improve the regional efficiency of energy utilisation and environmental quality. To illustrate the reasonability of our environmental efficiency results, we further construct an econometric model to investigate whether our FGL environmental efficiency scores $(D_{FGL(2)})$ will be influenced by such factors as the SO_2 abatement ratio, which is defined by the ratio of the annual volume of industrial SO_2 removed to total SO_2 emission (X_1); energy intensity, defined by the annual energy consumption per GDP (X_2); the annual investment in anti-pollution projects as the percentage of GDP (X_3); the ratio of annual pollution discharges levied to

GDP (X_4); and the ratio of annual expenditures for the indraught of technology to GDP (X_5). All the data of independent variables were all from 2006 to 2010 and were collected from "China Statistic Yearbook", "China Environment Yearbook", and further calculated by the author. The descriptive statistics of data is shown in Table 2.5 and the specific model form can be given following

$$D_{FGL(2)_{it}} = \beta_0 + \beta_1 X_{1,it} + \beta_2 X_{2,it} + \beta_3 X_{3,it} + \beta_4 X_{4,it} + \beta_5 X_{5,it} + u_{it} \tag{2.13}$$

where β_0 is the constant term; β_1, β_2, β_3, β_4 and β_5 are coefficient parameters of independent variables, respectively and u is the error term.

The regression results are listed in Table 2.6. We begin our analysis by estimating the coefficients of such influential factors using simple OLS, fixed effect (FE) and random effect (RE) models. Since our data set is panel data, the OLS may ignore the variations between different regions and lead to estimation bias. Hence the OLS result is only taken as a reference. Based on the Hausman test (Hausman, 1978), we decide to refer fixed effect model results to analyse which factors would affect our environmental efficiency scores. It can be observed that the SO_2 abatement ratio has a positive relationship with the environmental efficiency level, which can be explained as the fact that more efforts by the province will lead to a higher environmental efficiency level. In addition, the energy intensity shows a significant negative relationship with environmental efficiency, which indicates that if one unit of GDP produced requires more energy consumption, a lower environmental efficiency level will be reached. Therefore, readjusting the industrial structure for reducing the proportions of high energy consuming industries would be an effective way to improve the regional environmental efficiency, especially for some undeveloped western areas. However, our regression results also shows that expenditures for indraught of technology even has a significant negative effect on environmental efficiency. This result is consistent with the previous literature.[19] One possible explanation can be that the variable of expenditure for technology indraught might not concretely reflect the

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[19] Zeng (2011) uses the input-oriental variable return to scale (VRS) model based on the DEA efficiency measurement of Charnes et al. (1978) to measure China's regional total technical efficiency with bad output consideration. Then, it also employs Tobit regression and finds the technology innovation has a negative effect on regional technology efficiency.

expense of cleaning-technology or eco-friendly technology import and innovation. Furthermore, only expenditures on technology imports can not capture the real details of new technology applications. The internal technology development and absorptive capacity seem more important (Liao et al., 2012; Fisher-Vanden et al., 2006). Hence, local enterprises should remain cautious about introducing new technology from abroad and pay more attention to enhancing their research and development (R&D) strength based on their own situation of development in order to overcome the dependence on technology imports. When we add region dummies in Panel B and year dummies in Panel C in Table 2.5, the fixed effects estimation show consistent results.

Table 2.6: Regression Analysis of FGL Environmental Efficiency on Selected Impact Factors from 2006 to 2010

	FE	**RE**	**OLS**
Panel A: without dummies			
X_1	0.0836*	0.1427***	0.0270
	(0.049)	(0.039)	(0.052)
X_2	-0.1234***	-0.0541**	-0.0361*
	(0.039)	(0.026)	(0.018)
X_3	0.0109	0.0146	0.0439**
	(0.009)	(0.009)	(0.019)
X_4	0.0792	0.1126	0.4189***
	(0.124)	(0.118)	(0.143)
X_5	-0.0107*	-0.0125**	-0.0278**
	(0.006)	(0.006)	(0.011)
Constant	0.9382***	0.8042***	0.7957***
	(0.076)	(0.054)	(0.040)
Observations	150	150	150
$R-sq$	0.3786	0.3592	0.1128
Hausman Test (Chi-sq) 17.67***			
Panel B: with region dummies			
X_1	0.0836*	0.1539***	0.0500
	(0.049)	(0.041)	(0.051)
X_2	-0.1234***	-0.0415	0.0235
	(0.039)	(0.029)	(0.021)
X_3	0.0109	0.0152	0.0499***
	(0.009)	(0.009)	(0.018)
X_4	0.0792	0.1041	0.2276
	(0.124)	(0.121)	(0.139)
X_5	-0.0107*	-0.0129**	-0.0333***
	(0.006)	(0.006)	(0.010)
Constant	0.9382***	0.7521***	0.6432***
	(0.076)	(0.076)	(0.048)
Observations	150	150	150
$R-sq$	0.3786	0.3519	0.2552
Panel C: with year dummies			
X_1	0.1093*	0.1085*	-0.0156
	(0.064)	(0.058)	(0.059)
X_2	-0.1404***	-0.0491*	-0.0384**
	(0.044)	(0.027)	(0.018)
X_3	0.0151	0.0123	0.0372**
	(0.010)	(0.011)	(0.020)
X_4	0.0887	0.1186	0.4380***
	(0.127)	(0.121)	(0.144)
X_5	-0.0131*	-0.0131*	-0.0249**
	(0.007)	(0.007)	(0.012)
Constant	0.9542***	0.8073***	0.7941***
	(0.079)	(0.055)	(0.042)
Observations	150	150	150
$R-sq$	0.3893	0.3611	0.1307

Note: Robust standard errors in brackets
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

Meanwhile, our regression results also reveal that China's current environment regulations do not seem very effective in improving the regional environmental efficiency levels. The total investment in the treatment of environmental pollution and pollution discharge fees do not have significant effects on our environmental efficiency scores.

The reasons for the ineffectiveness of pollution treatment investments could be given as follows: First, the proportion of total investment to GDP in China is still very low (only 1.2% of GDP in 2005), and therefore this cannot play a proper role in the environmental efficiency improvement in a short term (Liu and Diamond, 2005). Second, the total investment in pollution treatment shows extremely unbalanced distribution across different regions. In 2010, the total investment in the eastern regions reached 369.94 billion CNY, which was even greater than the aggregation of three other areas, which had 256.87 billion.[20] This unreasonable funding allocation might lead to insufficiency in some areas but waste in other areas. Third, due to the lack of professionals with investment management experience, regional pollution control investment might not be planned and implemented reasonably. Hence, for achieving the effectiveness of environmental investment, local governments and relevant enterprises should be more focused on the purpose of the investment and the expected results, rather than ignoring investment.

In addition, even though China established a pollution discharge system, in particular, the discharge fees are still significantly lower than the abatement costs (OECD, 2006). According to statistics, the minimal discharge rates for SO_2 and NO_x are 0.63 CNY/kg and 0.60 CNY/kg in 2005, respectively.[21] Furthermore, the charges are only incurred for excess emissions, and there is no charge for the enterprises whose emissions are below the waste standards. Hence, it is difficult to stimulate enterprises to maximize emission reduction. In addition, Zhang et al. (2001) state that due to the environmental tax not being levied in China, the current environmental regulatory instruments will neither punish the enterprises which abide by the emission standards nor encourage them to seek for the low-cost pollution control technologies. Once environmental tax can be implemented,

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[20] Data from: statistical departments in Ministry of Environmental Protection and Ministry of Housing and Urban-rural Development, China.P.R.

[21] According to the latest statement from Ministry of Environmental Protection of Peoples' Republic of China, the new discharge rate will increase to 1.20 CNY/kg for main air pollutants.

every technology innovation means paying fewer taxes, which might be a new solution to improve the environmental efficiency of energy utilization.

In summary, according to our production and environmental efficiency measurement results, the reasons discussion has been carried out thoroughly. Through constructing the regression model, we concentrate on explaining which factors influence regional environmental efficiency and find some shortcomings in China's current environment policy. In addition, some other effective measures to improve environmental efficiency could also be analysed further, such as the decomposition of the effect factors of elimination policy on different air pollutants from the regional or industrial perspective (Fujii et al., 2013). Furthermore, it is also necessary to examine the relationship between income or economic growth and environmental quality (Stern et al., 1996; Harbaugh et al., 2002; Rezek and Rogers, 2008); and decompose the determinants of environmental performance or consider whether environmental policy could be more stringent when the technique effect could not sufficiently reduce emissions (Panayotou, 1997; Tsurumi and Managi, 2010).

2.4 Conclusions

This chapter introduces a by-production approach to modeling emission generating technologies. Under BP approach, decomposition of pollution generating technologies based on the multiple production relations can better capture the phenomenon of by production generating than the traditional weak-disposability approach with a single production relationship. This chapter also employs the modified HYP and FGL efficiency indexes under BP to investigate China's regional technical efficiency with due consideration being given to generation of pollution by provinces from 2006 to 2010. By classifying four economic areas, the eastcoast area had the most effective performance in desirable output generation, but the west performed worst in both desirable output and undesirable output efficiency measurements. Furthermore, the production efficiency gaps between the four areas are very significant, but in environmental efficiency this characteristic is not so obvious. Through conducting a reason discussion, we also found that the environmental efficiency levels were significantly affected by SO_2 abatement activities and energy intensity, but the environment policy factors were shown as being less robust. Furthermore, this chapter also demonstrates that China's regional technical efficiency levels are consistent with the regional disparity development pattern and the ineffectiveness of the implementation of current environmental regulations.

According to our findings, we can provide some policy implications. First, due to such differences in regional development, the Chinese central government should release more rights of decision making to sub-national local governments and support them to design more suitable policies for their own local development. Since uniform planing or standards are widely used in China's environmental regulation system, some drawbacks of relying on uniform standards might inevitably impact the effectiveness of environmental governance. Therefore, it requires policy makers to pay more attention to key regions with lower efficiency levels and ensure the environmental regulations in different regions are used more purposefully and pertinently. Second, there is a negative effect between the energy intensity and environmental efficiency level. Adjusting and changing the industrial structure from the high energy consumption industries to high value-added service or technology industries will play a key role in emission reduction and in improving regional environmental efficiency. Third, the current environmental regulations which involve pollution charges and investment in anti-pollution projects have not achieved the predicted effects. All levels of government and environmental regulators need to constantly improve the level of management in the pollution charge system, to ensure the discharge process is reasonable, and meets the real needs of local development. Meanwhile, policy makers should accelerate and promote the enforcement of environmental taxation in China at an appropriate time, which would be a good supplement to the environment pollution charge regulation.

Appendix

Table 2.7: Table of HYP Production Efficiency ($D_{HYP(1)}$) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	0.8480	0.9007	1.0000	1.0000	1.0000
Tianjin	0.8024	0.8004	0.8256	0.8587	0.8727
Hebei	0.9194	0.9611	0.9856	0.9746	0.9364
Shanxi	0.7246	0.7139	0.6843	0.6081	0.5857
Inner Mongolia	0.7106	0.7008	0.7131	0.7153	0.7082
Liaoning	0.9145	0.9183	0.9250	0.9966	1.0000
Jilin	0.7558	0.7224	0.6911	0.6690	0.6532
Heilongjiang	0.9762	0.9644	0.9639	0.9536	0.9455
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangsu	1.0000	1.0000	1.0000	1.0000	1.0000
Zhejiang	0.9616	0.9443	0.9311	0.9063	0.9651
Anhui	1.0000	1.0000	1.0000	1.0000	1.0000
Fujian	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangxi	0.8217	0.9379	0.9150	1.0000	1.0000
Shandong	0.9044	0.9762	0.9806	1.0000	1.0000
Henan	1.0000	0.9596	0.9317	0.9363	0.9361
Hubei	1.0000	1.0000	0.9978	1.0000	1.0000
Hunan	0.9664	0.9752	0.9925	0.9623	1.0000
Guangdong	1.0000	1.0000	1.0000	1.0000	1.0000
Guangxi	0.8716	0.8577	0.8530	1.0000	1.0000
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000
Chongqing	0.6805	0.6809	0.6762	0.6959	0.7236
Sichuang	0.9350	0.9255	0.8673	0.8590	0.8796
Guizhou	0.6218	0.6316	0.6320	0.6544	0.7074
Yunnan	0.6884	0.6717	0.6924	0.7413	0.8401
Shaanxi	0.5901	0.5863	0.5725	0.5650	0.5640
Gansu	0.8134	0.8177	0.7717	0.7565	0.7490
Qinghai	0.5478	0.5360	0.5455	0.5298	0.5394
Ningxia	0.4373	0.4358	0.4289	0.4207	0.4158
Xinjiang	0.5458	0.5379	0.5631	0.5713	0.5710

Table 2.8: Table of HYP Environmental Efficiency ($D_{HYP(2)}$) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	1.0000	1.0000	1.0000	1.0000	1.0000
Tianjin	0.8142	0.8322	0.8802	0.9408	0.8552
Hebei	0.7354	0.7956	0.7741	0.8828	0.8706
Shanxi	1.0000	1.0000	1.0000	1.0000	1.0000
Inner Mongolia	1.0000	0.9956	1.0000	1.0000	1.0000
Liaoning	0.6479	0.6615	0.6959	0.7089	0.7459
Jilin	0.8746	0.8666	0.9649	0.9835	1.0000
Heilongjiang	0.9576	0.9969	0.9878	0.9749	1.0000
Shanghai	0.7281	0.7445	0.7896	0.8426	0.8849
Jiangsu	0.7590	0.8499	0.8761	0.8478	0.8585
Zhejiang	0.9118	0.9023	0.9260	0.8923	0.9547
Anhui	0.8304	0.8947	0.9294	0.9470	0.9759
Fujian	0.9706	1.0000	1.0000	0.8959	0.9270
Jiangxi	0.7536	0.8170	0.8378	0.8085	0.8893
Shandong	0.8414	0.8811	0.9009	0.9050	0.8985
Henan	0.7880	0.9128	0.9472	0.9497	0.9404
Hubei	0.9523	1.0000	1.0000	1.0000	0.9905
Hunan	0.7681	0.9014	0.8849	0.8937	0.9037
Guangdong	1.0000	1.0000	1.0000	1.0000	1.0000
Guangxi	0.9457	0.9293	0.9806	0.9661	0.9697
Hainan	1.0000	1.0000	1.0000	1.0000	0.9681
Chongqing	1.0000	1.0000	1.0000	1.0000	1.0000
Sichuang	0.9047	0.9361	0.9917	0.9948	0.9857
Guizhou	0.6800	0.8918	1.0000	1.0000	1.0000
Yunnan	0.8421	0.9115	0.9419	0.9514	1.0000
Shaanxi	0.7197	0.8255	0.8841	0.8654	0.8616
Gansu	0.5258	0.6645	0.6965	0.6875	0.7165
Qinghai	0.9260	1.0000	1.0000	1.0000	1.0000
Ningxia	0.7500	0.9736	0.9885	1.0000	1.0000
Xinjiang	0.7509	0.8657	0.8202	0.8455	0.8686

Table 2.9: Table of Integrated HYP Efficiency (D_{HYP}) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	1.0000	1.0000	1.0000	1.0000	1.0000
Tianjin	0.8142	0.8322	0.8802	0.9408	0.8727
Hebei	0.9194	0.9611	0.9856	0.9746	0.9364
Shanxi	1.0000	1.0000	1.0000	1.0000	1.0000
Inner Mongolia	1.0000	0.9956	1.0000	1.0000	1.0000
Liaoning	0.9145	0.9183	0.9250	0.9966	1.0000
Jilin	0.8746	0.8666	0.9649	0.9835	1.0000
Heilongjiang	0.9762	0.9969	0.9878	0.9749	1.0000
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangsu	1.0000	1.0000	1.0000	1.0000	1.0000
Zhejiang	0.9616	0.9443	0.9311	0.9063	0.9651
Anhui	1.0000	1.0000	1.0000	1.0000	1.0000
Fujian	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangxi	0.8217	0.9379	0.9150	1.0000	1.0000
Shandong	0.9044	0.9762	0.9806	1.0000	1.0000
Henan	1.0000	0.9596	0.9472	0.9497	0.9404
Hubei	1.0000	1.0000	1.0000	1.0000	1.0000
Hunan	0.9664	0.9752	0.9925	0.9623	1.0000
Guangdong	1.0000	1.0000	1.0000	1.0000	1.0000
Guangxi	0.9457	0.9293	0.9806	1.0000	1.0000
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000
Chongqing	1.0000	1.0000	1.0000	1.0000	1.0000
Sichuang	0.9350	0.9361	0.9917	0.9948	0.9857
Guizhou	0.6800	0.8918	1.0000	1.0000	1.0000
Yunnan	0.8421	0.9115	0.9419	0.9514	1.0000
Shaanxi	0.7197	0.8255	0.8841	0.8654	0.8616
Gansu	0.8134	0.8177	0.7717	0.7565	0.7490
Qinghai	0.9260	1.0000	1.0000	1.0000	1.0000
Ningxia	0.7500	0.9736	0.9885	1.0000	1.0000
Xinjiang	0.7509	0.8657	0.8202	0.8455	0.8686

Table 2.10: Table of FGL Production Efficiency ($D_{FGL(1)}$) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	0.8480	0.9007	1.0000	1.0000	1.0000
Tianjin	0.8024	0.8004	0.8256	0.8587	0.8727
Hebei	0.9194	0.9611	0.9856	0.9746	0.9364
Shanxi	0.7246	0.7139	0.6843	0.6081	0.5857
Inner Mongolia	0.7106	0.7008	0.7131	0.7153	0.7082
Liaoning	0.9145	0.9183	0.9250	0.9966	1.0000
Jilin	0.7558	0.7224	0.6911	0.6690	0.6532
Heilongjiang	0.9762	0.9644	0.9639	0.9536	0.9455
Shanghai	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangsu	1.0000	1.0000	1.0000	1.0000	1.0000
Zhejiang	0.9616	0.9443	0.9311	0.9063	0.9651
Anhui	1.0000	1.0000	1.0000	1.0000	1.0000
Fujian	1.0000	1.0000	1.0000	1.0000	1.0000
Jiangxi	0.8217	0.9379	0.9150	1.0000	1.0000
Shandong	0.9044	0.9762	0.9806	1.0000	1.0000
Henan	1.0000	0.9596	0.9317	0.9363	0.9361
Hubei	1.0000	1.0000	0.9978	1.0000	1.0000
Hunan	0.9664	0.9752	0.9925	0.9623	1.0000
Guangdong	1.0000	1.0000	1.0000	1.0000	1.0000
Guangxi	0.8716	0.8577	0.8530	1.0000	1.0000
Hainan	1.0000	1.0000	1.0000	1.0000	1.0000
Chongqing	0.6805	0.6809	0.6762	0.6959	0.7236
Sichuang	0.9350	0.9255	0.8673	0.8590	0.8796
Guizhou	0.6218	0.6316	0.6320	0.6544	0.7074
Yunnan	0.6884	0.6717	0.6924	0.7413	0.8401
Shaanxi	0.5901	0.5863	0.5725	0.5650	0.5640
Gansu	0.8134	0.8177	0.7717	0.7565	0.7490
Qinghai	0.5478	0.5360	0.5455	0.5298	0.5394
Ningxia	0.4373	0.4358	0.4289	0.4207	0.4158
Xinjiang	0.5458	0.5379	0.5631	0.5713	0.5710

Table 2.11: Table of FGL Environmental Efficiency ($D_{FGL(2)}$) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	1.0000	1.0000	1.0000	1.0000	1.0000
Tianjin	0.7634	0.7524	0.7710	0.8761	0.7726
Hebei	0.7257	0.7660	0.7731	0.8503	0.8702
Shanxi	1.0000	1.0000	1.0000	1.0000	1.0000
Inner Mongolia	1.0000	0.8138	0.8565	0.8874	0.9402
Liaoning	0.6284	0.6129	0.6335	0.6755	0.6919
Jilin	0.8590	0.8370	0.9528	0.9795	1.0000
Heilongjiang	0.9160	0.9228	0.9435	0.9468	0.9724
Shanghai	0.6366	0.6439	0.6811	0.7593	0.8039
Jiangsu	0.7486	0.7689	0.7905	0.7987	0.8107
Zhejiang	0.7769	0.8118	0.8081	0.8268	0.8324
Anhui	0.8218	0.8216	0.8890	0.9428	0.9667
Fujian	0.8036	0.8538	0.8414	0.8054	0.7748
Jiangxi	0.6221	0.6489	0.6480	0.6387	0.7006
Shandong	0.8238	0.8418	0.8718	0.8970	0.8808
Henan	0.7814	0.7904	0.8310	0.8632	0.8961
Hubei	0.8522	0.8978	0.8543	0.9155	0.9271
Hunan	0.7399	0.7612	0.7524	0.7797	0.7861
Guangdong	0.8022	0.7482	0.7309	0.7413	0.7844
Guangxi	0.6369	0.6224	0.6396	0.6308	0.6494
Hainan	1.0000	1.0000	1.0000	0.9927	0.8888
Chongqing	0.7101	0.8648	0.7447	0.7567	0.7717
Sichuang	0.7119	0.8181	0.7478	0.7676	0.7520
Guizhou	0.6091	0.6663	0.7686	0.8441	0.8443
Yunnan	0.8270	0.8185	0.8381	0.8851	0.8848
Shaanxi	0.6181	0.6506	0.6613	0.6844	0.7353
Gansu	0.5233	0.5515	0.5745	0.5649	0.5981
Qinghai	0.7472	0.8819	0.8067	0.7967	0.7468
Ningxia	0.6886	0.7656	0.7671	0.8368	0.9121
Xinjiang	0.6698	0.6931	0.6507	0.7108	0.7225

Table 2.12: Table of Integrated FGL Efficiency (D_{FGL}) under BP Technologies

Regions	**2006**	**2007**	**2008**	**2009**	**2010**
Beijing	0.9240	0.9503	1.0000	1.0000	1.0000
Tianjin	0.7829	0.7764	0.7983	0.8674	0.8226
Hebei	0.8226	0.8635	0.8793	0.9125	0.9033
Shanxi	0.8623	0.8569	0.8421	0.8041	0.7929
Inner Mongolia	0.8553	0.7573	0.7848	0.8013	0.8242
Liaoning	0.7715	0.7656	0.7793	0.8361	0.8459
Jilin	0.8074	0.7797	0.8219	0.8242	0.8266
Heilongjiang	0.9461	0.9436	0.9537	0.9502	0.9590
Shanghai	0.8183	0.8219	0.8406	0.8797	0.9019
Jiangsu	0.8743	0.8845	0.8953	0.8994	0.9054
Zhejiang	0.8692	0.8780	0.8696	0.8665	0.8988
Anhui	0.9109	0.9108	0.9445	0.9714	0.9833
Fujian	0.9018	0.9269	0.9207	0.9027	0.8874
Jiangxi	0.7219	0.7934	0.7815	0.8193	0.8503
Shandong	0.8641	0.9090	0.9262	0.9485	0.9404
Henan	0.8907	0.8750	0.8814	0.8998	0.9161
Hubei	0.9261	0.9489	0.9261	0.9577	0.9636
Hunan	0.8532	0.8682	0.8724	0.8710	0.8931
Guangdong	0.9011	0.8741	0.8655	0.8707	0.8922
Guangxi	0.7543	0.7401	0.7463	0.8154	0.8247
Hainan	1.0000	1.0000	1.0000	0.9963	0.9444
Chongqing	0.6953	0.7729	0.7104	0.7263	0.7476
Sichuang	0.8235	0.8718	0.8076	0.8133	0.8158
Guizhou	0.6155	0.6489	0.7003	0.7492	0.7759
Yunnan	0.7577	0.7451	0.7653	0.8132	0.8625
Shaanxi	0.6041	0.6184	0.6169	0.6247	0.6496
Gansu	0.6684	0.6846	0.6731	0.6607	0.6736
Qinghai	0.6475	0.7090	0.6761	0.6633	0.6431
Ningxia	0.5630	0.6007	0.5980	0.6287	0.6639
Xinjiang	0.6078	0.6155	0.6069	0.6410	0.6467

Chapter 3

Designing Consumption-increasing and Emission Non-increasing Input Policy Reforms[1]

3.1 Introduction

In a recent paper, Murty (2016) argues that the intuitive and well-studied trade-offs between economic objectives (such as increasing output, standards of living, profits, *etc.*), and environmental objectives (such as reducing emission levels) are binding only when economic units *optimally* allocate their resources subject to institutional and environmental constraints. In the presence of inefficiencies in resource allocation, such trade-offs weaken considerable generating scope for promotion of *both* economic and environmental objectives. Using data from 118 countries, Murty (2016) demonstrates the prevalence of allocative inefficiencies and proposes a methodology based on policy reforms to construct reforms that result both in increasing profit (producer surplus) and in decreasing the level of CO_2 emission of a country whose present status-quo is inefficient.[2]

In the literature, computation of the marginal abatement cost (MAC) is also based on the assumption that economic units maximise their economic objectives subject to the institutional and environmental constraints they face. Typically, the envelope theorem is applied to derive MAC as the reduction in the maximised value of the objective function

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[1] The work in this chapter is joint with my supervisor Professor Sushama Murty.

[2] The concept of a policy reform was developed in public economics in the context of second-best taxation theory. Second-best optimal taxes were characterised by Diamond and Mirrlees (1971) in their seminal papers. The tax reform literature took the view that the current status-quo will usually not be second-best optimal and radical instantaneous changes in the tax system with a view to attain the second-best optimum will often be institutionally and politically infeasible. Rather, what could be more practical and achievable are local/marginal changes (*i.e.,* marginal tax reforms) in the status-quo tax rates. The literature studies welfare improvements induced by such local changes in tax rates/marginal tax reforms. For the original thinking and conceptualisation of these ideas, see, Feldstein (1976), Guesnerie (1977, 1995), Diewert (1978), and Weymark (1978, 1979). For their empirical and theoretical applications, see Ahmad and Stern (1984), Murty and Ray (1989), Myles (1995) p.167-195, Blackorby and Brett (2000), and Murty and Russell (2005). These works have greatly motivated and influenced the analysis in this chapter.

of the economic unit due to a unit reduction in its level of emission. However, it will rarely be the case that the current status-quo of an economic unit is a result of optimising behaviour. There is little empirical evidence that rules out non-optimising behaviour. At the same time, the movement from a currently inefficient status-quo to the optimal allocation will generally involve a discrete jump, which may not be institutionally feasible or politically acceptable. For this reason, in the real world, efficiency improvements are often piecemeal or incremental. The focus hence shifts to efficiency improvements that can be achieved by policy reforms that take us to a small/local neighbourhood of the status-quo. Using this argument, Murty (2016, 2015a) defines a measure of MAC that is based on such local policy reforms: it is defined as the reduction in the maximum profit that the economic unit can achieve by adopting policies that lie in the local neighbourhood of its status-quo, per unit reduction in its emission level.

This chapter builds on Murty (2016). As in Murty (2016), it adopts the by-production approach of Murty et al. (2012), Murty (2015b), and Murty and Russell (2016) to modelling emission generating technologies. The main differences with Murty (2016) model in this chapter are, firstly, highlighting the central role played by the energy sector in both the generation and mitigation of emission and delineating three key properties of the energy input, it extends the Murty (2016) model to incorporate a more detailed modelling of the energy sector. Secondly, Murty (2016) restricts the model to studying the profit motive, *i.e.*, the objective of economic units to increase their producer surpluses. Under this objectives, Murty (2016) gives two extremes, in between these two extremes are reforms that not only increase the economic units' profits but also simultaneously reduce its emission. Our paper focuses the consumption output motive, and develop a structure of methodology to test the existence of such reforms, which can induce production units' consumption outputs increasing without non-emission increasing. Thirdly, the theory developed in this chapter is relevant for economic units such as sub-national entities rather than national entities in Murty (2016), aiming to increase resources diverted to final consumption subject to meeting emission targets. [3]

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[3] A follow-up research applies the theory developed in this work to study the scope and nature of efficiency improvements in provinces in China.

Employing this model, this chapter provides a theoretical characterisation for the existence of final consumption-increasing local reforms that are feasible, given the existing economic resources and the existing state of the technology, and do not lead to increases in emission generation. The model construction is based on an assumption of which production units operating with technical efficiency but *allocative inefficiency*. Given inputs allocative inefficiencies, at the current status-quo, it becomes possible to re-allocate inputs to increase consumption (apart from final desirable production) and without increasing emission level.[4] The existence of such input policy reforms is an indicator of allocative inefficiencies at the status-quo of the economic unit. We, hence, call such reforms *efficiency-improving reforms*. We develop a methodology for empirically testing for the existence of efficiency-improving reforms at the status-quo using data available at the status-quo. If such reforms exist, we derive the formula to compute the optimal reform (*i.e.,* the feasible and emission non-increasing local reform that leads to the greatest increase in final consumption expenditure) using status-quo data. In the framework of local reforms, we also derive formulae to compute the MAC of the economic unit based on data available at the status-quo.

Another contribution of this work is that it provides a framework to study the structures (compositions) of efficiency-improving reforms at an inefficient status-quo. For example, we could study if all efficiency-improving reforms necessarily imply reducing fossil-fuel usage OR if such reforms entail increases in fossil-fuel usage accompanied by increases also in carbon sequestration activities such as afforestation. Existence of feasible, emission non-increasing, and final consumption-increasing reforms with such hypothesised additional features can also be empirically tested using the methodology we develop.

Section 3.2 lays down the model and notation. The policy instruments studied in this chapter are described in Section 3.3, while Section 3.4 describes what we mean by a policy reform and defines feasible, final consumption-increasing, and emission-non increasing reforms. Section 3.5 extends the reform framework developed in Section 3.4

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[4] The assumption of allocative efficiency concerns mix of inputs, and there is no technical inefficiency by assumption. It may connect to the Porter Hypothesis of a "win-win" situation in case of technical inefficiency. *See*, Brännlund and Lundgren (2009).

to incorporate restrictions on reforms in addition to feasibility, no increase in emission generation, and increase in final consumption expenditure. Section 3.6 provides (i) a general theoretical characterisation of efficiency improving reforms with possible additional features, (ii) an empirical methodology for testing these general existence conditions at the status-quo, and (iii) a methodology to compute the optimal local reform in the general framework. Section 3.7 focuses on the special case of pure efficiency-improving reforms, *i.e.,* reforms that are final consumption-increasing, feasible, and emission non-increasing and derives a measure of MAC based on local reforms; while Section 8 studies the case of efficiency-improving reforms with additional structure. Section 3.9 concludes.

3.2 The Model and Some Maintained Assumptions

3.2.1 The Model

The model presented below adopts the by-production approach of Murty et al. (2012), Murty (2015b), Murty and Russell (2016) to modelling emission generating technologies. This approach is based on the work of Frisch (1965). As opposed to the conventional single equation approach to the functional representations of production technology sets, Frisch argued that, in many situations, production technologies involve several production relations between inputs and outputs, each of which can be represented by a separate function. Førsund (2009) shows how Frisch's ideas are relevant for modelling emission generating technologies.

The by-production approach distinguishes between emission-causing and non-emission causing inputs. It models an emission generating technology as an intersection of two technologies, one defined by standard relations in production that describe the transformation of standard inputs of a producing unit into its intended outputs, while the other is defined by relationships that exist in nature between emissions and emission-causing inputs used by a producing units and by the extent of emission mitigation made possible by various human abatement efforts. For this reason, we will call the former technology, the "intended-output producing technology" of the producing unit and the latter technology "nature's emission-generating mechanism".

Energy is an important input into intended-output production. Firstly, it is an essential input of intended-output production (in most cases, no intended output can be produced when this input is absent). Secondly, it restricts the amount of intended output that can be produced; in other words, it is a limitational input – there are limits to the increase in intended output when the energy input is held fixed even if the other inputs such as labour and capital are allowed to increase arbitrarily, and thirdly, its use is highly complementary to the use of other inputs – *e.g.,* increasing the usage of machines requires concomitant increase in the energy input.[5]

At the same time, the energy sector plays a crucial role in both the generation and the mitigation of emissions. Energy can be derived from many sources. Currently, the most economically viable but environmentally detrimental sources are fossil fuels as combustion of these generates both energy and emissions. However, by changing to energy sources such as renewables and other clean fuels, emission generation can be mitigated.

Hence, a detailed modelling of the energy sector is warranted while studying emission control policies and their effects on production of intended outputs. In this regards, the economy's resources such as capital and labour are shared by both the non-energy and the energy sectors, while producing intended outputs. The energy output is used partly to meet the final consumption demand for energy and is partly used by the non-energy sector as an intermediate input.

In our model, we would like to incorporate all the above features of the energy sector. To do so, requires specifying the production function of the energy sector, which will have to be estimated in empirical applications. Estimation of the energy production function requires data on inputs such as labour, capital, and raw materials such as fossil fuels employed by this sector.

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[5] The general concept of limitationality of an input is defined in Shephard (1970). We believe that this concept is especially relevant for the energy input.

The model, below, is designed keeping in mind the constraints posed by the nature and coverage of relevant province-level data available in China, as in a follow-up chapter, we apply this theory to study scope for efficiency improvements in these provinces and to compute their MACs. As the coverage of data increases in future, the model can be adjusted and improved further.

Production Structure of the Energy Sector

The total amounts of labour and capital inputs, denoted by l and k, respectively, are divided between the production of final output, denoted by GDP, and the intermediate output of energy, denoted by e. Energy can be derived from fossil-fuels or renewable resources.

Total energy consumed is the sum of energy produced plus net import of energy. Total energy produced is the sum of electrical and non-electrical energy produced. We assume that electrical energy can be produced by using coal, gas, and renewable resources.[6] Non-electrical energy can be derived from all fossil-fuels. Coal, gas, and oil comprise the set of fossil-fuels.

The electrical energy generated by coal and gas is thermal energy, denoted by e_T, while the amount of electrical energy generated from renewable (alternative) sources is denoted by e_R.[7] The non-electrical energy generated by oil is denoted by e_O. Non-electrical energy generated from coal and gas is denoted by e_{NC} and e_{NG}. Hence, total energy produced, measured in energy units such as kilotons of oil equivalents, is given by

$$e_{PROD} = e_T + e_R + e_O + e_{NC} + e_{NG}, \qquad e_T = e_{TC} + e_{TG},$$

where e_{TC} and e_{TG} denote thermal energy generated from coal and gas, respectively. Suppose net import of energy is denoted by $e_{NM} = e_{IMP} - e_{EXP}$, where e_{IMP} and e_{EXP} denote, respectively, the energy imported and the energy exported. Then total energy

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[6] Oil is generally not a big cost-effective source of electrical energy.

[7] In this chapter renewable (alternative) energy includes solar, hydro, and wind energy as well as nuclear energy. The terms "renewable" and "alternative" sources of energy are used interchangeably in this work.

consumed is given by

$$e = e_{PROD} + e_{NM} = e_T + e_R + e_O + e_{NC} + e_{NG} + e_{NM}. \tag{3.1}$$

The amounts of the three fossil-fuels, coal, gas, and oil, utilised are denoted by x_C, x_G, and x_O, respectively. The utilisation of coal and gas can be decomposed into

$$\begin{aligned} x_C &= x_{TC} + x_{NC} \\ x_G &= x_{TG} + x_{NG}, \end{aligned}$$

where, for $i = C, G$, x_{Ti} is the amount of fossil fuel i going into thermal (electrical) energy generation and x_{Ni} is the amount of fossil fuel i going into non-electrical energy generation.

Estimation of the production function of the energy sector requires data on inputs such as labour, capital, and raw materials such as fossil fuels. Unfortunately, we could not find data on total labour and capital employed by the aggregate energy sectors of provinces in China. A limited amount of information on input usage in coal-using thermal electricity generation and renewable energy generating sector can be inferred from currently available data sources. So we posit a conventional production function for coal-fired and renewable electricity generation.

Thermal energy production from coal requires capital, labour, and coal as inputs. According to IEA statistics, 75.4% of thermal electricity currently generated in China was from coal-fired plants in 2013.[8] Labour and capital employed in coal-fired power plants are denoted by l_{TC} and k_{TC}, respectively. The production function characterising net electricity generation in coal-fired plants is given by

$$e_{TC} = E^C(k_{TC}, l_{TC}, x_{TC}). \tag{3.2}$$

With respect to renewable energy, we assume that the stock of renewable resource is

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[8] Though recently, there is a move to introduce more gas-fired electricity producing power plants in China. According to the data from National Energy Administration of China, the total gas-fired electricity generation is around 109,200 million kWh, and accounts for only 2.19% of national total electricity generation in China.

fixed, but the amount of energy derived from it depends on the extent to which it is tapped using labour and capital resources.[9] The amounts of labour and capital devoted to the production of energy from renewable sources are denoted by l_R and k_R, respectively. The production function characterising net electricity generation from renewables is given by

$$e_R = E^R(k_R, l_R). \tag{3.3}$$

But for other sources of energy such as electrical energy produced in gas-fired plants and non-electrical energy produced from coal and gas data on labour and capital resources used is not available. Hence, we are not able to posit similar conventional production functions for these sources of energy. Rather, we had to relate the generation of energy from these sources directly to the heat content of fossil fuels and efficiency conversion factors.

Adopting definitions in data sources such as the U.S. Energy Information Administration (EIA), we measure thermal energy generated from gas directly from the usage of gas and the heat-rate of gas-fired power plants as

$$e_{TG} = \frac{\epsilon_G}{h_{TG}} x_{TG}, \tag{3.4}$$

where ϵ_G is the *heat factor* of gas, *i.e.,* the amount of heat (energy) produced by one unit of gas. Due to inefficiencies, not all of the heat energy so generated is converted into electricity. The *heat rate* of gas-fired plants, denoted by h_{TG}, is the amount of energy required to produce one unit of electrical energy.[10]

Hence, total net thermal energy production from coal and gas is given by

$$e_T = E^C(k_{TC}, l_{TC}, x_{TC}) + \frac{\epsilon_G}{h_{TG}} x_{TG}. \tag{3.5}$$

Since data on labour and capital resources into non-electrical energy sector are currently not available, we once again measure the output of this sector directly in terms of the

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[9] While no fuels are used in generating solar, hydro, and wind energy, lack of data on fuel usage in the nuclear power plant makes us focus only on capital and labour resources employed by the total renewable (alternative) energy sector.

[10] Heat rate of a power plant is an indicator of the efficiency of the power plant – the smaller the heat rate, the more efficient is the power plant.

fossil-fuel usage and heat rates in this sector. Thus, non-electrical energy from coal, gas, and oil are assumed to be given by

$$e_O = \frac{\epsilon_O}{h_O} x_O, \quad e_{NC} = \frac{\epsilon_C}{h_{NC}} x_{NC} = \varepsilon_{NC} \epsilon_{NC} x_{NC}, \quad e_{NG} = \frac{\epsilon_G}{h_{NG}} x_{NG} = \varepsilon_{NG} \epsilon_{NG} x_{NG}, \tag{3.6}$$

where ϵ_O, ϵ_C, and ϵ_G are the energy factors of oil, coal, and gas, respectively, while h_O, h_{NC}, and h_{NG} are the heat rates of oil, coal, and gas used in this sector, respectively, *i.e.,* for $i = O, C, G$, these are the amounts of energy required to produce one of unit non-electrical energy from fossil fuel i. The inverse of the heat-rate of non-electrical energy generation from fossil fuel i, which is here denoted by ε_i, is the efficiency of generating non-electrical energy from fossil-fuel i.[11]

From (3.1), it follows that

$$e = e_T + E^R(k_R, l_R) + \frac{\epsilon_O}{h_O} x_O + \frac{\epsilon_C}{h_{NC}} x_{NC} + \frac{\epsilon_G}{h_{NG}} x_{NG} + e_{NM}. \tag{3.7}$$

Various Costs

Afforestation provides a means of sequestering carbon generated by combustion of fossil fuels and hence a means of mitigating emissions generated by the production process. However, maintaining existing forests and increasing forest cover by afforestation efforts are costly. The stock of forest inherited at the beginning of the year and the ex-ante extent of afforestation planned for the year are denoted by f and a, respectively. Forest related expenditure is given by the function

$$G^{af} = \Phi(a, f + a), \tag{3.8}$$

which indicates that forest related expenditure every year depends on both the plans for afforestation (a) during the year and the expenditure on maintaining the current year's stock of forests $(f + a)$.

In the absence of data on labour and capital employed in gas-fired electricity and non-

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[11] In our empirical analysis, we assume $h_O = 1$ (full efficiency of generating energy from oil), while efficiency factors ε_{NC} and ε_{NG} are derived from the REMIND model of IAM, 2015 (Luderer et al., 2015).

electrical energy generation, the comprehensive costs of generating energy from these sources was computed from estimates of levelized costs, and we assume that these costs are financed out of the value of output produced by each province.

In our empirical application, we employ the estimate provided by several sources such as the Nuclear Energy Agency (NEA) and US EIA and Integrated Assessment Models such as REMIND, of the levalized (per-unit monetary) costs of generating (LCOG) energy from these sources. The LCOG electricity from gas-fired plants and the LCOG non-electrical energy from coal and gas are denoted by ξ_{TG}, ξ_{NC}, and ξ_{NG}, respectively. The estimates of LCOG energy include both capital, labour, and fuel costs. Hence, the total costs of producing electricity from gas-fired plants and non-electrical energies from coal and gas are given by

$$G^{TG} = \xi_{TG}e_{TG} = \xi_{TG}\frac{\epsilon_G}{h_{TG}}x_{TG},\ G^{NC} = \xi_{NC}e_{NC} = \xi_{NC}\frac{\epsilon_C}{h_{NC}}x_{NC}, \\ G^{NG} = \xi_{NG}e_{NG} = \xi_{NG}\frac{\epsilon_G}{h_{NG}}x_{NG}. \tag{3.9}$$

The market prices of oil and coal are p_O and p_C, respectively. Oil is mainly used in producing non-electrical and non-stationary energy (it is used mainly in the transport sector). We assume that capital and labour costs of producing non-stationary energy are negligible and measure only its fuel cost, which is given from (3.6) as

$$G^{x_O} = p_O x_O = p_O e_O \frac{h_O}{\epsilon_O}. \tag{3.10}$$

The cost of fossil-fuel used in coal-fired plant is given by

$$G^{x_{TC}} = p_C x_{TC}, \tag{3.11}$$

The Final Consumption Expenditure and Resource Constraints

We assume that l_Y and k_Y are the total amounts of labour and capital, respectively, devoted to the production of output in all sectors other than the renewable energy sector and coal-fired thermal energy sector. The aggregation of all these other sectors will be called sector $\mathcal{Y}$. Employing labour l_Y, capital k_Y, and total energy e generated by the aggregate energy sector, sector $\mathcal{Y}$ produces an aggregate output, denoted by Y (measured in monetary units). Sector $\mathcal{Y}$'s production function is

$$Y = F\left(k_Y, l_Y, e\right). \tag{3.12}$$

Using an input-output argument, it can be shown that the value Y created by sector $\mathcal{Y}$ finances (i) the final consumption requirements (for meeting the final demand) of the year denoted by y,[12] (ii) the forest-related expenditures of the government and (iii) the costs of generating gas-powered electricity, non-electrical energy from coal and gas, and the fuel costs of coal-fired plants and of oil in the non-stationary energy sector. Hence,

$$\begin{aligned} Y = F\left(k_Y, l_Y, e\right) &= y + G^{af} + G^{TG} + G^{NC} + G^{NG} + G^{x_{TC}} + G^{x_O} \\ &= y + \Phi(a, f+a) + \xi_{TG}\frac{\epsilon_G}{h_{TG}}x_{TG} + \xi_{NC}\frac{\epsilon_C}{h_{NC}}x_{NC} + \xi_{NG}\frac{\epsilon_G}{h_{NG}}x_{NG} \\ &\qquad + p_C x_{TC} + p_O x_O. \qquad\qquad (3.13) \\ &= GDP + \xi_{TG}\frac{\epsilon_G}{h_{TG}}x_{TG} + \xi_{NC}\frac{\epsilon_C}{h_{NC}}x_{NC} + \xi_{NG}\frac{\epsilon_G}{h_{NG}}x_{NG} + p_C x_{TC} + p_O x_O, \end{aligned}$$

where, following conventional definition, $GDP = y + G^{af}$. In the empirical application of the theory developed here, we will estimate the production function F using the last equality in (3.13).

We will be interested in feasible input reforms that can finance increases in final consumption expenditure y. This is obtained from the second equality of (3.13) as

$$\begin{aligned} y &= F\left(k_Y, l_Y, e\right) - \Phi(a, f+a) - \xi_{TG}\frac{\epsilon_G}{h_{TG}}x_{TG} - \xi_{NC}\frac{\epsilon_C}{h_{NC}}x_{NC} - \xi_{NG}\frac{\epsilon_G}{h_{NG}}x_{NG} \\ &\qquad - p_C x_{TC} - p_O x_O. \end{aligned} \tag{3.14}$$

The following resource constraints on capital and labour help to capture the relative costs of labour and capital resources used in the thermal and renewable energy sectors and in sector $\mathcal{Y}$; precisely, allocating more of these resources to one sector comes at the cost of reducing these inputs to (and hence outputs of) the other sectors.[13]

$$k = k_Y + k_{TC} + k_R \qquad \text{and} \qquad l = l_Y + l_{TC} + l_R. \tag{3.15}$$

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[12] This includes governmental consumption expenditure under all heads other than forest expenditure. We will also refer to y as the level of final consumption expenditure.

[13] Recall that k and l are the total endowments of capital and labour available.

Emission Generation

The previous sections described the technological relations between inputs and outputs in intended production component of the by-production technology underlying our analysis.

We now describe the emission generating mechanism component of our by-production technology. The emission factors of fossil-fuels coal, gas, and oil are denoted by α_C, α_G, and α_O, respectively. Each measures the amount of carbon emitted by a unit combustion of the given fossil fuel in electrical and non-electrical energy generation. Afforestation results in carbon sequestration. The amount of carbon sequestered every year is reflected in the addition to the stock of forests (the afforestation level) every year. We assume that a unit of afforestation sequesters s amount of carbon. Hence, the *net* emission generated is given by

$$z_n = \alpha_C[x_{TC} + x_{NC}] + \alpha_G[x_{TG} + x_{NG}] + \alpha_O x_O - sa. \tag{3.16}$$

3.2.2 Maintained Assumptions

We will maintain the following set of assumptions throughout the chapter. These include standard monotonicity conditions on the postulated production and cost functions and positivity of all heat rates and emission, sequestration, and efficiency conversion factors of various fossil fuels.

Assumptions

(i) The production function $F : \mathbf{R}^3_+ \longrightarrow \mathbf{R}_+$ is twice continuously differentiable in the interior of its domain and strictly concave. For all $\langle k_Y, l_Y, e \rangle \in \mathbf{R}^3_{++}$, we have $F_l > 0$, $F_k > 0$, and $F_e > 0$.[14]

(ii) The function $E^C : \mathbf{R}^3_+ \longrightarrow \mathbf{R}_+$ is twice continuously differentiable in the interior

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[14] F_l, F_k, F_e denote the partial derivatives of function F with respect to labour, capital, and energy, respectively.

of its domain and strictly concave. For all $\langle k_C, l_C, x_C \rangle \in \mathbf{R}^3_{++}$, we have $E^C_l > 0$, $E^C_k > 0$, and $E^C_x > 0$.

(iii) The function $E^R : \mathbf{R}^2_+ \longrightarrow \mathbf{R}_+$ is twice continuously differentiable in the interior of its domain and strictly concave. For all $\langle k_R, l_R \rangle \in \mathbf{R}^2_{++}$, we have $E^R_l > 0$ and $E^R_k > 0$.

(iv) The function $\Phi : \mathbf{R}^2_+ \longrightarrow \mathbf{R}_+$ is continuously differentiable in the interior of its domain and convex. For all $\langle a, f \rangle \in \mathbf{R}^2_{++}$, we have $\Phi_a > 0$ and $\Phi_f > 0$.

(v) $\alpha_i > 0$ for $i = C, G, O$, $\quad s > 0, \quad h_G > 0, \quad h_O > 0, \quad h_{NC} > 0, \quad h_{NG} > 0,$ $\epsilon_G > 0 \quad \epsilon_C > 0,$ and $\epsilon_O > 0$.

(vi) $p_O > 0, p_C > 0, \xi_{TG} > 0, \xi_{NC} > 0,$ and $\xi_{NG} > 0$.

3.3 Environmental Policy Instruments, Feasible Allocations, and A Status-quo.

The policy reform approach adopted in this chapter is based on a short-run analysis involving currently available data. In the short-run, the prices of fossil-fuels, the levelized costs of producing electrical energy from gas and non-electrical energy from coal and gas, the stock of forest, the endowments of capital and labour, and the net import of energy are assumed to be held fixed. In other words, these variables are assumed to be exogenous and they define the basic environment within which reforms in other policy variables are designed. A vector of these exogenous variables is denoted by $\Theta = \langle p_C, p_G, p_O, \xi_G, \xi_{NC}, \xi_{NG}, f, k, l, e_{NM} \rangle \in \mathbf{R}^{10}_{++}$.[15] As in Murty (2016), the central question is whether it is possible to do better starting from the status-quo (the current

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[15] We will adopt both vector and matrix notations in this chapter. Vector notation, which is employed in Sections 2 to 4, is helpful in making notation more compact and, hence, to save space. In vector notation, a vector $a \in \mathbf{R}^n$ is denoted as $\langle a_1, \ldots, a_n \rangle$. Matrix notation is used from Section 5 onwards. When using matrix notation, all vectors are column vectors so that $a = \begin{bmatrix} a_1 \\ \vdots \\ a_n \end{bmatrix}$. The dot product of two vectors a and b in $\mathbf{R}^n$ is denoted in vector notation as $a \cdot b$, while in matrix notation it is $a^\top b$ where, given a matrix A, $A^\top$ denotes the transpose of matrix A.

position) of the producing unit (which in our context is a province in China). In the context of this work, this amounts to asking whether it is possible for a province to increase output devoted to final consumption expenditure (y), while at the same time meet its emission targets, where possible emission targets could include reducing emission below the status-quo level or maintaining status-quo level of emission. Existence of potentials for such improvements is an indicator of allocative inefficiencies prevailing at the status-quo.

We distinguish between three types of policy variables available for reforms (i) an emission cap, denoted by $z \in \mathbf{R}_+$, which is reviewed and independently changed by the policy maker, (ii) a vector of active policy variables, denoted by
$\nu = \langle \nu_1, \nu_2, \ldots, \nu_{13} \rangle \in \mathbf{R}^{13}_+$ with elements

$$\nu = \langle k_Y, k_C, k_R, l_Y, l_C, l_R, e_T, x_{TC}, x_{TG}, x_{NC}, x_{NG}, x_O, a \rangle =: \langle \nu_1, \nu_2, \ldots, \nu_{13} \rangle \in \mathbf{R}^{13}_+,$$

and (iii) a policy on the level of final consumption expenditure $y \in \mathbf{R}_+$ to meet the final demand. Taking the vector of exogenous factors Θ as given, by influencing variables (instruments) of active policy, the policy maker can influence the allocation of labour and capital resources into energy and non-energy sectors, the production of thermal and renewable electrical energy, the production of non-electrical energy from various fossil-fuels, and the afforestation level. It is clear that changes in active policies influence intended production and, hence, the output that can be devoted to final consumption y. At the same time they also affect net emission generation. In fact, changes in active policies are required to ensure that any policy change in the emission cap and the final consumption expenditure can be met.

It is to be noted that our policy variables are quantity based. Murty (2016) argues that, at a first stage of planning, the policy makers often formulate policies in terms of quantity targets, *e.g.,* the planner may have emission and consumption targets and, at the same time, may identify a suitable combination of input policies (*e.g.,* reducing fossil-fuel usage and encouraging afforestation and renewable energy generation) to achieve these targets. At the second stage of implementation, the planner may consider price and/or quantity incentives to meet planned input goals to achieve planned emission and consumption targets. For example, price incentives to meet input goals may include taxing fossil fuels or subsidising renewable energy costs if the policy maker plans to reduce emission. Thus, this chapter is concerned with the first-stage of the planning process, and hence focuses on quantity based policies.

An *allocation* is a vector of levels of active policy variables, the emission cap, and the level of final consumption expenditure, denoted by $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$. Given the vector of exogenous variables Θ, an allocation $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$, with

$$\nu = \langle k_Y, k_C, k_R, l_Y, l_C, l_R, e_T, x_{TC}, x_{TG}, x_{NC}, x_{NG}, x_O, a \rangle = \langle \nu_1, \nu_2, \ldots, \nu_{13} \rangle$$

, is a *feasible allocation* if

$$\begin{aligned}
F\left(k_Y, l_Y, e_T + E^R(k_R, l_R) + \frac{\epsilon_O}{h_O} x_O + \frac{\epsilon_C}{h_{NC}} x_{NC} + \frac{\epsilon_G}{h_{NG}} x_{NG} + e_{NM}\right) & \\
-\Phi(a, f+a) - p_O x_O - p_C x_{TC} - \xi_{TG} \frac{\epsilon_G}{h_G} x_{TG} - \xi_{NC} \frac{\epsilon_C}{h_{NC}} x_{NC} - \xi_{NG} \frac{\epsilon_G}{h_{NG}} x_{NG} & \geq y \\
\alpha_C [x_{TC} + x_{NC}] + \alpha_G [x_{TG} + x_{NG}] + \alpha_O x_O - sa & \leq z \\
E^C(k_{TC}, l_{TC}, x_{TC}) + \frac{\epsilon_G}{h_{TG}} x_{TG} & \geq e_T \\
k_Y + k_{TC} + k_R & \leq k \\
l_Y + l_{TC} + l_R & \leq l
\end{aligned} \tag{3.17}$$

Thus, the allocation $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$ is feasible, if the vector of active policies ν can produce at least y level of final consumption expenditure (see (3.14)) without generating emission level greater than the emission cap z (see (3.16)). This is the message of the first two inequalities in (3.17). We can interpret e_T as the demand for thermal energy in the production of output Y in sector $\mathcal{Y}$, so that the third inequality in (3.17) says that the demand for thermal energy e_T should be less than its production (see (3.5)). Similarly, the fourth and the fifth inequalities requires the allocation to respect the labour and capital resource constraints based on (3.15). A feasible allocation $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$ is *tightly feasible* if all inequalities in (3.17) hold as equalities.

A status-quo, denoted by $\langle \Theta, \nu, y, z \rangle \in \mathbf{R}_+^{25}$, consists of a vector of exogenous variables and a the feasible allocation that describe the current state of the world in terms of current data on the exogenous variable vector $\Theta \in \mathbf{R}_+^{10}$ and the policy variable vector $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$. At the status-quo, $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$ is a feasible allocation given Θ. A status-quo $\langle \Theta, \nu, y, z \rangle \in \mathbf{R}_+^{25}$ is tight if $\langle \nu, y, z \rangle \in \mathbf{R}_+^{15}$ is a tightly feasible vector of active policies given Θ.

3.4 Policy Reforms

In this section, we define a policy reform and characterise feasible, final consumption-increasing, and environmentally permissible policy reforms.

3.4.1 Reforms in Active Policies and the Emission Cap

Given a vector of exogenous variables $\Theta = \langle p_C, p_G, p_O, \xi_G, \xi_{NC}, \xi_{NG}, f, k, l, e_{NM} \rangle \in \mathbf{R}_{++}^{10}$, we first define the following functions based on (3.13), (3.7), (3.5), (3.16), and (3.15):

$$\begin{aligned}
\mathcal{F} \quad &: \quad \mathbf{R}_+^{13} \longrightarrow \mathbf{R} \quad \text{with image} \\
y = \mathcal{F}(\nu) \quad &= \quad F\left(k_Y, l_Y, e_T + E^R(k_R, l_R) + \frac{\epsilon_O}{h_O} x_O + \frac{\epsilon_C}{h_{NC}} x_{NC} + \frac{\epsilon_G}{h_{NG}} x_{NG} + e_{NM}\right) \\
&\quad -\Phi(a, f + a) - p_O x_O - p_C x_{TC} \\
&\quad -\xi_{TG} \frac{\epsilon_G}{h_G} x_{TG} - \xi_{NC} \frac{\epsilon_C}{h_{NC}} x_{NC} - \xi_{NG} \frac{\epsilon_G}{h_{NG}} x_{NG} \\
\mathcal{Z} \quad &: \quad \mathbf{R}_+^{13} \longrightarrow \mathbf{R} \quad \text{with image} \\
z_n = \mathcal{Z}(\nu) \quad &= \quad \alpha_C [x_{TC} + x_{NC}] + \alpha_G [x_{TG} + x_{NG}] + \alpha_O x_O - sa \qquad (3.18) \\
\mathcal{T} \quad &: \quad \mathbf{R}_+^{13} \longrightarrow \mathbf{R} \quad \text{with image} \\
\zeta_{e_T} = \mathcal{T}(\nu) \quad &= \quad e_T - E^C(k_{TC}, l_{TC}, x_{TC}) - \frac{\epsilon_G}{h_{TG}} x_{TG} \\
\mathcal{K} \quad &: \quad \mathbf{R}_+^{13} \longrightarrow \mathbf{R} \quad \text{with image} \\
\zeta_k = \mathcal{K}(\nu) \quad &= \quad k_{TC} + k_R + k_Y - k \\
\mathcal{L} \quad &: \quad \mathbf{R}_+^{13} \longrightarrow \mathbf{R} \quad \text{with image} \\
\zeta_l = \mathcal{L}(\nu) \quad &= \quad l_{TC} + l_R + l_Y - l
\end{aligned}$$

Given an active policy vector $\nu = \langle k_Y, k_C, k_R, l_Y, l_C, l_R, e_T, x_{TC}, x_{TG}, x_{NC}, x_{NG}, x_O, a\rangle \in \mathbf{R}_+^{13}$, function $\mathcal{F}$ measures the final consumption expenditure made possible by ν (it is the difference in output produced in sector $\mathcal{Y}$ and various costs incurred by this sector), function $\mathcal{Z}$ measures the net emission generated by ν, function $\mathcal{T}$ measures the excess demand for thermal energy under ν, while functions $\mathcal{K}$ and $\mathcal{L}$ measure the excess demands for capital and labour resources under ν.

Let $\langle \Theta, \bar{\nu}, \bar{y}, \bar{z}\rangle$ be a tight status-quo. Starting from this status-quo, a reform in active policies (riap) is a differential change in the vector of active policies:

$$\begin{aligned} d\nu &= \langle dk_Y, dk_C, dk_R, dl_y, dl_C, dl_R, de_T, dx_{TC}, dx_{TG}, dx_{NC}, dx_{NG}, dx_O, da\rangle \in \mathbf{R}^{13} \\ &=: \langle d\nu_1, \ldots, d\nu_{13}\rangle \end{aligned}$$

A riap induces differential changes in the levels of final consumption expenditure, net emission, excess demands for thermal energy, and capital and labour inputs. These are given by[16]

$$\begin{aligned} &dy = \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot d\nu, \quad dz_n = \nabla_\nu \mathcal{Z}(\bar{\nu}) \cdot d\nu, \\ &d\zeta_{e_T} = \nabla_\nu \mathcal{T}(\bar{\nu}) \cdot d\nu, \quad d\zeta_k = \nabla_\nu \mathcal{K}(\bar{\nu}) \cdot d\nu, \quad d\zeta_l = \nabla_\nu \mathcal{L}(\bar{\nu}) \cdot d\nu. \end{aligned}$$

Employing the chain rule of differentiation, we now show that differential changes dy, dz_n, $d\zeta_{e_T}$, $d\zeta_k$, and $d\zeta_l$ can be more rigorously interpreted as derivatives of functions $\mathcal{F}$, $\mathcal{Z}$, $\mathcal{T}$, $\mathcal{K}$, and $\mathcal{L}$, resp., along linear policy paths. Given a riap $d\nu \in \mathbf{R}^{13}$, define a linear policy path starting from the status-quo in the direction of riap $d\nu$ as a vector-valued function $\nu : \mathbf{R} \longrightarrow \mathbf{R}_+^{13}$ with image

$$\begin{aligned} \big\langle \nu_1(t), \ldots, \nu_{13}(t)\big\rangle &\equiv \nu(t) = \bar{\nu} + d\nu\, t \\ &= \langle \bar{\nu}_1, \ldots, \bar{\nu}_{13}\rangle + \langle d\nu_1, \ldots, d\nu_{13}\rangle\, t \end{aligned}$$

Thus, this path starts at the status-quo as $\nu(0) = \bar{\nu}$, in a direction of vector $d\nu$, and is parametrised by variable t. The vector of derivatives of functions $\nu_1(t), \ldots, \nu_{13}(t)$ with

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[16] $\nabla_\nu \mathcal{F}(\bar{\nu})$ denotes the gradient of function $\mathcal{F}$ with respect to all active policies evaluated at a policy vector $\bar{\nu}$. Similarly, we can define the gradients of all other functions in (3.18) evaluated at the status-quo.

respect to t is denoted by

$$\begin{aligned} \dot{\nu} \quad &\equiv \quad \langle \dot{k}_Y, \dot{k}_C, \dot{k}_R, \dot{l}_Y, \dot{l}_C, \dot{l}_R, \dot{e}_T, \dot{x}_{TC}, \dot{x}_{TG}, \dot{x}_{NC}, \dot{x}_{NG}, \dot{x}_O, \dot{a} \rangle = \langle \dot{\nu}_1, \dot{\nu}_2, \ldots, \dot{\nu}_{13} \rangle. \\ &\Longrightarrow \quad \dot{\nu} = d\nu. \end{aligned} \tag{3.19}$$

Thus, the vector of derivatives $\dot{\nu}$ is exactly equal to the riap $d\nu$.

Functions $\mathcal{F}$, $\mathcal{Z}$, $\mathcal{T}$, $\mathcal{K}$, and $\mathcal{L}$ evaluated along the policy path $\nu(t)$ are given by

$$y(t) = \mathcal{F}\left(\nu(t)\right), \quad z_n(t) = \mathcal{Z}\left(\nu(t)\right), \quad \zeta_{e_T} = \mathcal{T}\left(\nu(t)\right), \quad \zeta_k = \mathcal{K}\left(\nu(t)\right), \quad \zeta_l = \mathcal{L}\left(\nu(t)\right).$$

Applying the chain rule, the derivatives of these functions along the linear path $\nu(t)$ evaluated at status-quo active policy vector $\bar{\nu}$ are given by

$$\begin{aligned} \frac{\partial y}{\partial t} \quad &\equiv \quad \dot{y} = \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot \dot{\nu} = \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot d\nu = dy, \\ \frac{\partial z_n}{\partial t} \quad &\equiv \quad \dot{z}_n = \nabla_\nu \mathcal{Z}(\bar{\nu}) \cdot \dot{\nu} = \nabla_\nu \mathcal{Z}(\bar{\nu}) \cdot d\nu = dz_n, \\ \frac{\partial \zeta_{e_T}}{\partial t} \quad &\equiv \quad \dot{\zeta}_{e_T} = \nabla_\nu \mathcal{T}(\bar{\nu}) \cdot \dot{\nu} = \nabla_\nu \mathcal{T}(\bar{\nu}) \cdot d\nu = d\zeta_{e_T}, \\ \frac{\partial \zeta_k}{\partial t} \quad &\equiv \quad \dot{\zeta}_k = \nabla_\nu \mathcal{K}(\bar{\nu}) \cdot \dot{\nu} = \nabla_\nu \mathcal{K}(\bar{\nu}) \cdot d\nu = d\zeta_k, \\ \frac{\partial \zeta_l}{\partial t} \quad &\equiv \quad \dot{\zeta}_l = \nabla_\nu \mathcal{L}(\bar{\nu}) \cdot \dot{\nu} = \nabla_\nu \mathcal{L}(\bar{\nu}) \cdot d\nu = d\zeta_l. \end{aligned} \tag{3.20}$$

Hence, it follows from (3.19) and (3.20) that the differential changes dy, dz_n, $d\zeta_{e_T}$, $d\zeta_k$, and $d\zeta_l$ due to riap $d\nu$ can be interpreted as derivatives of functions $\mathcal{F}$, $\mathcal{Z}$, $\mathcal{T}$, $\mathcal{K}$, and $\mathcal{L}$, resp., along the linear policy path $\nu(t)$ in the direction of reform vector $d\nu = \dot{\nu}$.

Hence, in what follows, we will use the notation $\dot{\nu}$ and $d\nu$ interchangeably to denote a reform in active policies.

Similarly a reform in the emission cap is a differential change in the emission cap and is denoted by dz. Further, we can define a linear path in the emission space starting from the status-quo level of the emission cap in the direction of reform dz as a function $z : \mathbf{R} \longrightarrow \mathbf{R}_+$ with image

$$z(t) = \bar{z} + dz\, t.$$

Thus, this path starts at the status-quo level of emission (as $z(0) = \bar{z}$), has slope dz, and is parametrised by variable t. Hence, the derivative of function $z(t)$ is $\dot{z} = dz$. Hence, we will use the notation $\dot{z}$ and dz interchangeably to denote a reform in the emission cap.

3.4.2 Feasible, Consumption-increasing, Permissible, and Emission Non-increasing Reforms

Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ be a tight status-quo. This implies that at s, there capital and labour resources are fully utilised and the thermal electrical energy consumed by sector $\mathcal{Y}$ is exactly equal to its production:

$$\begin{aligned}
E^C(k_{TC}, l_{TC}, \bar{x}_{TC}) + \frac{\epsilon_G}{h_{TG}} \bar{x}_{TG} &= \bar{e}_T & \iff \quad & \mathcal{T}(\bar{\nu}) = 0 \\
\bar{k}_Y + \bar{k}_{TC} + \bar{k}_R &= k & \iff \quad & \mathcal{K}(\bar{\nu}) = 0 \\
\bar{l}_Y + \bar{l}_{TC} + \bar{l}_R &= l & \iff \quad & \mathcal{L}(\bar{\nu}) = 0,
\end{aligned}$$

where $\mathcal{T}$, $\mathcal{L}$, and $\mathcal{K}$ are as defined in (3.18).

Starting from s, a riap $\dot{\nu} \in \mathbf{R}^{13}$ is *feasible* if it does not result in differential increases in the excess demands for thermal energy, capital, and labour, *i.e.,* $\dot{\nu}$ is feasible if

$$\dot{\zeta}_{e_T} = \nabla_\nu \mathcal{T}(\bar{\nu}) \cdot \dot{\nu} \leq 0, \qquad \dot{\zeta}_k = \nabla_\nu \mathcal{K}(\bar{\nu}) \cdot \dot{\nu} \leq 0, \qquad \dot{\zeta}_l = \nabla_\nu \mathcal{L}(\bar{\nu}) \cdot \dot{\nu} \leq 0. \quad (3.21)$$

At the tight status-quo $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$, the output of sector $\mathcal{Y}$ that is available for final consumption is exactly equal to $\bar{y}$:

$$\begin{aligned}
& F\left(\bar{k}_Y, \bar{l}_Y, \bar{e}_T + E^R(\bar{k}_R, \bar{l}_R) + \frac{\epsilon_O}{h_O} \bar{x}_O + \frac{\epsilon_C}{h_{NC}} \bar{x}_{NC} + \frac{\epsilon_G}{h_{NG}} \bar{x}_{NG} + \bar{e}_{NM} \right) \\
& \quad - \Phi(\bar{a}, f + \bar{a}) - p_O \bar{x}_O - p_C \bar{x}_{TC} - \xi_{TG} \frac{\epsilon_G}{h_G} \bar{x}_{TG} - \xi_{NC} \frac{\epsilon_C}{h_{NC}} \bar{x}_{NC} - \xi_{NG} \frac{\epsilon_G}{h_{NG}} \bar{x}_{NG} \; = \; \bar{y}
\end{aligned}$$

Starting from s, a riap $\dot{\nu} \in \mathbf{R}^{13}$ is *final consumption-increasing* if it results in a differential increase in final expenditure, *i.e.,*

$$\dot{y} := \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot \dot{\nu} > 0, \quad (3.22)$$

where $\mathcal{F}$ is as defined in (3.18).

At the tight status-quo $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$, the net emission generated at the status-quo is exactly equal to the emission cap at the status-quo:

$$\alpha_C[\bar{x}_{TC} + \bar{x}_{NC}] + \alpha_G[\bar{x}_{TG} + \bar{x}_{NG}] + \alpha_O\bar{x}_O - s\bar{a} \;\;=\;\; \bar{z} \qquad \Longleftrightarrow \qquad \mathcal{Z}\left(\bar{\nu}\right) = \bar{z},$$

where $\mathcal{Z}$ is as defined in (3.18).

Starting from s and an exogenously given reform in the emission cap $\dot{z}$, a riap $\dot{\nu} \in \mathbf{R}^{13}$ is *permissible* if the differential change in net emission that it induces is no bigger than $\dot{z}$, *i.e.,*

$$\dot{z}_n := \nabla_\nu \mathcal{Z}(\bar{\nu}) \cdot \dot{\nu} \leq \dot{z}, \tag{3.23}$$

Starting from s, a riap $\dot{\nu} \in \mathbf{R}^{13}$ is *emission non-increasing*, if it does not result in any differential increase in net emission, *i.e.,*

$$\nabla_\nu \mathcal{Z}(\bar{\nu}) \cdot \dot{\nu} \leq 0. \tag{3.24}$$

Using the matrix notation, the gradients of all the functions in (3.18) with respect to all the active policy variables k_Y, k_C, k_R, l_Y, l_C, l_R, e_T, x_{TC}, x_{TG}, x_{NC}, x_{NG}, x_O, and a are

$$\begin{aligned}
\nabla_\nu \mathcal{F}(\bar{\nu}) &= \Big\langle F_k,\ 0,\ F_e E_k^R,\ F_l,\ 0,\ F_e E_l^R,\ F_e,\ -p_C,\ -\xi_G \frac{\epsilon_G}{h_{TG}}, \\
&\qquad \frac{\epsilon_C}{h_{NC}}[F_e - \xi_C],\ \frac{\epsilon_G}{h_{NG}}[F_e - \xi_G],\ F_e \frac{\epsilon_O}{h_O} - p_O,\ -[\Phi_a + \Phi_f] \Big\rangle \\
\nabla_\nu \mathcal{Z}(\bar{\nu}) &= \langle 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ \alpha_C,\ \alpha_G,\ \alpha_C,\ \alpha_G,\ \alpha_O,\ -s \rangle \qquad (3.25) \\
\nabla_\nu \mathcal{T}(\bar{\nu}) &= \Big\langle 0,\ -E_k^C,\ 0,\ 0,\ -E_l^C,\ 0,\ 1,\ -E_x^C,\ -\frac{\epsilon_G}{h_{TG}},\ 0,\ 0,\ 0,\ 0 \Big\rangle \\
\nabla_\nu \mathcal{K}(\bar{\nu}) &= \langle 1,\ 1,\ 1,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0 \rangle \\
\nabla_\nu \mathcal{L}(\bar{\nu}) &= \langle 0,\ 0,\ 0,\ 1,\ 1,\ 1,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0 \rangle .
\end{aligned}$$

3.5 Modelling Additional Restrictions on Reforms

In addition to feasibility, permissibility, and ensuring increase in final expenditure, a riap may also be subject to other (linear) constraints. For example, we will study later whether there can exist reforms that are feasible, non-emission increasing, final consumption-increasing and, at the same time, consistent with increases in usage of fossil-fuels.[17] In particular, lets focus on the simple case where there is only one additional linear constraint on riaps, which takes the form:[18]

$$I^{\top}\dot{\nu} \; < \; 0 \qquad \text{OR} \tag{3.26}$$

$$I^{\top}\dot{\nu} \; \leq \; 0. \tag{3.27}$$

where I is a column vector with 13 elements.[19] Define a matrix X of dimension $13 \times (4 + m)$, where m can take two values: $m = 0$ or $m = 1$, as follows:

When $m = 0$, then[20]

$$X = \begin{bmatrix} X_1 & X_2 & X_3 & X_4 \end{bmatrix} \quad \equiv \quad \boldsymbol{\chi} \quad = \quad \begin{bmatrix} \nabla_{\nu}\mathcal{Z}(\bar{\nu}) & \nabla_{\nu}\mathcal{T}(\bar{\nu}) & \nabla_{\nu}\mathcal{K}(\bar{\nu}) & \nabla_{\nu}\mathcal{L}(\bar{\nu}) \end{bmatrix}, \tag{3.28}$$

When $m = 1$, then

$$X = \begin{bmatrix} X_1 & X_2 & X_3 & X_4 & X_5 \end{bmatrix} \equiv \begin{bmatrix} \boldsymbol{\chi} & I \end{bmatrix} \tag{3.29}$$

Suppose $\dot{z}$ is an exogenously given differential change in the emission cap. Let ρ be a 4-dimensional column vector, whose first element is $\dot{z}$ and all other elements are zero.

Using the constructs X and ρ, we can define possible constraints on a riap. Given a reform $\dot{z}$ in the emission cap, starting from the tight status-quo s, it follows from (3.21)

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[17] Such reforms could exist, for example, if increases in fossil fuels is accompanied by increase also in afforestation, as the latter mitigates increases in emission generation due to increased usage of fossil-fuels.

[18] Starting from this section, we will use matrix notation. All vectors, from now on, are column vectors.

[19] For example, if we require that the riap $\dot{\nu}$ should also satisfy the additional constraint that it should lead to a decrease in thermal energy, then I is a column vector with all elements, other than the seventh element, equal to zero. The seventh element corresponds to the position for the active policy variable e_T. Given $\dot{\nu}^{\top} = \begin{bmatrix} \dot{k}_Y \; \dot{k}_C \; \dot{k}_R \; \dot{i}_Y \; \dot{i}_C \; \dot{i}_R \; \dot{e}_T \; \dot{x}_{TC} \; \dot{x}_{TG} \; \dot{x}_{NG} \; \dot{x}_O \; \dot{a} \end{bmatrix}$, $I^{\top}\dot{\nu} < 0$ implies $\dot{e}_T < 0$.

[20] Using the matrix notation, $\nabla_{\nu}\mathcal{Z}(\bar{\nu})$, $\nabla_{\nu}\mathcal{T}(\bar{\nu})$, $\nabla_{\nu}\mathcal{K}(\bar{\nu})$, and $\nabla_{\nu}\mathcal{L}(\bar{\nu})$ are column vectors with each having 13 elements.

and (3.23), that a riap $\dot{\nu}$ is permissible and feasible if[21]

$$\begin{bmatrix} \nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{T}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \end{bmatrix} \dot{\nu} \le \begin{bmatrix} \dot{z} \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \Longleftrightarrow \qquad X^\top \dot{\nu} \le \rho,$$

where X is given by (3.28), *i.e.*, this corresponds to the case where $m = 0$.

Starting from the tight status-quo s, it follows from (3.21) and (3.23), that a riap $\dot{\nu}$ is emission non-increasing and feasible if[22]

$$\begin{bmatrix} \nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{T}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \end{bmatrix} \dot{\nu} \le \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \Longleftrightarrow \qquad X^\top \dot{\nu} \le 0_4, \tag{3.30}$$

where X is given by (3.28), *i.e.*, this corresponds to the case where $m = 0$.

Given a reform $\dot{z}$ in the emission cap, starting from the tight status-quo s, a riap $\dot{\nu}$ is feasible, permissible, and satisfies constraint (3.27) if

$$\begin{bmatrix} \nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{T}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \\ I^\top \end{bmatrix} \dot{\nu} \le \begin{bmatrix} \dot{z} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \Longleftrightarrow \qquad X^\top \dot{\nu} \le \begin{bmatrix} \rho \\ 0 \end{bmatrix}, \tag{3.31}$$

where X is given by (3.29), *i.e.*, this corresponds to the case where $m = 1$.

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[21] Notation for vector inequalities: for any two vectors $a = \langle a_1, \dots, a_n \rangle$ and $b = \langle b_1, \dots, b_n \rangle$ in an arbitrary Euclidean space $\mathbf{R}^n$,

$$\begin{aligned} a \ge b &\iff a_i \ge b_i \; \forall\, i = 1, \dots, n, \\ a > b &\iff a_i \ge b_i \; \forall\, i = 1, \dots, n \text{ with } a \ne b, \text{ and} \\ a \gg b &\iff a_i > b_i \; \forall\, i = 1, \dots, n. \end{aligned}$$

.

[22] A n-dimensional zero column vector is denoted by 0_n.

Starting from the tight status-quo s, a riap $\dot{\nu}$ is emission non-increasing, feasible, and satisfies constraint (3.27) if

$$\begin{bmatrix} \nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{T}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \\ \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \\ I^\top \end{bmatrix} \dot{\nu} \leq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \Longleftrightarrow \qquad X^\top \dot{\nu} \leq 0_5, \tag{3.32}$$

where X is given by (3.29), *i.e.,* this corresponds to the case where $m = 1$.

3.6 Constrained Consumption-increasing Reforms: A General Formulation

We will be interested in studying the theoretical conditions for existence of riaps that are final consumption-increasing, feasible, emission non-increasing, and possibly also satisfying some other additional constraint.[23] We will also be interested in empirically testing for the existence of such reforms using data available at the status-quo and in identifying the optimal reform in this set, *i.e.,* the reform in this set that leads to the maximum increase in final expenditure.

3.6.1 Existence of Constrained Consumption-increasing Reforms: A General Result

We use the Motzkin's theorem of the alternative (MTA) to characterise the general existence conditions for reforms that are final consumption-increasing, feasible, emission non-increasing, and possibly also (depending on whether $m = 0$ or $m = 1$) satisfying some other additional constraint. This theorem, as any theorem of alternative, states that either there exists a solution to a set of linear inequalities or there exists a solution to a corresponding set of linear equalities.[24]

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[23] The plurals of reform in active policies (riap) is denoted, by riaps.

[24] See, for instance, Mangasarian (1969), p.34.

THEOREM OF THE ALTERNATIVE (MTA) (MOTZKIN (1936): *Let* A*,* C*, and* D *be* $n_1 \times m$*,* $n_2 \times m$*, and* $n_3 \times m$ *matrices, where* A *is non vacuous. Then, there exists a vector* $x \in \mathbf{R}^m$ *satisfying*

$$Ax \gg 0_{n_1}, \quad Cx \geq 0_{n_2}, \quad \textit{and} \quad Dx = 0_{n_3}$$

if and only if there do not exist vectors, $y^1 \in \mathbf{R}^{n_1}$*,* $y^2 \in \mathbf{R}^{n_2}$*, and* $y^3 \in \mathbf{R}^{n_3}$*, satisfying*

$$A^\top y^1 + C^\top y^2 + D^\top y^3 = 0_m, \quad y^1 > 0_{n_1}, \quad y^2 \geq 0_{n_2}.$$

Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ be a tight status-quo. Define vector Y as

$$Y := \nabla_\nu^\top \mathcal{F}(\bar{\nu}) \in \mathbf{R}^{13}.$$

Starting from s, suppose we seek the existence of riap of a reform vector $\dot{\nu} \in \mathbf{R}^{13}$ that satisfies

$$\begin{aligned} Y^\top \dot{\nu} &> 0 \\ -X^\top \dot{\nu} &\geq 0_{4+m} \end{aligned} \tag{3.33}$$

In particular, if $m = 0$, then (3.33) is equivalent to seeking the existence of a reform vector $\dot{\nu} \in \mathbf{R}^{13}$ that is feasible, emission-non increasing and final consumption-increasing, *i.e.,* $\dot{\nu}$ satisfies:

$$\begin{aligned} Y^\top \dot{\nu} &> 0 \\ -\boldsymbol{\chi}^\top \dot{\nu} &\geq 0_4, \end{aligned} \tag{3.34}$$

and if $m = 1$, then (3.33) is equivalent to seeking the existence of a reform vector $\dot{\nu} \in \mathbf{R}^{13}$ that is feasible, emission-non increasing, final consumption-increasing, and also satisfies an additional linear constraint *i.e.,* $\dot{\nu}$ satisfies:

$$\begin{aligned} Y^\top \dot{\nu} &> 0 \\ -\boldsymbol{\chi}^\top \dot{\nu} &\geq 0_4 \\ -I^\top \dot{\nu} &\geq 0 \end{aligned} \tag{3.35}$$

MTA can directly be applied to characterise existence of reforms that satisfies (3.33) with matrix $A = Y^\top$, matrix $C = -X^\top$, and matrix D is vacuous. The following lemma is a direct application of the MTA.

Lemma 1 *Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ be a tight status-quo. Then, there exists a riap $\dot{\nu} \in \mathbf{R}^{13}$ that satisfies (3.33) if and only if there do not exist $\lambda_Y > 0$ and $\langle \lambda_1,\ \lambda_2, \ldots, \lambda_{4+m} \rangle \geq 0_{4+m}$ such that*

$$\lambda_Y Y - \sum_{i=1}^{4+m} \lambda_i X_i = 0_{13}, \tag{3.36}$$

where $m = 0$ if X is given by (3.28) and $m = 1$ if X is given by (3.29).

3.6.2 Empirical Test for Existence of Constrained Consumption-increasing Reforms and Computing the Optimal Reform: A Useful General Result

We introduce the concept of a local/marginal riap. A local riap is a vector of differential changes in active policies that, starting from a tight status-quo, results in a vector of active policies that lies in a local neighbourhood of the status-quo. Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ be a tight status-quo. The following programme considers all riaps that lead to active policy vectors in a local neighbourhood of size one around s. Thus, all such riaps lie within the unit ball (*i.e.*, satisfy $\|\dot{\nu}\| \leq 1$, which is equivalent to $\dot{\nu}^\top \dot{\nu} \leq 1$).[25] Suppose $\dot{z} \in \mathbf{R}$ is an exogenously given differential change in the emission cap. The programme searches in the unit ball for the reform that is feasible, permissible, satisfies a possible additional constraint, and leads to the greatest differential increase in final expenditure.

$$\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) := \max_{\dot{\nu} \in \mathbf{R}^{13}} Y^\top \dot{\nu}$$

$$\text{subject to}$$

$$X^\top \dot{\nu} \leq \hat{\rho} \quad \text{and} \quad \dot{\nu}^\top \dot{\nu} \leq 1, \tag{3.37}$$

where $\hat{\rho} = \rho$ when $m = 0$ (the case when no additional constraint is included) and $\hat{\rho} = \begin{bmatrix} \rho \\ 0 \end{bmatrix}$ when $m = 1$ (the case when there is an additional constraint of the form (3.27)).

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[25] If a riap $\dot{\nu}$ has length less than or equal to one, *i.e.*, $\|\dot{\nu}\| \leq 1$, then the active policy vector that it leads to starting from the status-quo is $\bar{\nu} + \dot{\nu} \in \mathbf{R}^{13}$ and this new active policy vector lies within a unit radius around the status-quo active policy vector $\bar{\nu}$, *i.e.*, it lies in a neighbourhood of length one around $\bar{\nu}$.

Thus, depending on whether or not we are including a constraint in addition to feasibility and permissibility (*i.e.,* whether $m = 0$ or $m = 1$, resp.), matrix X is given by (3.28) or (3.29).

Recall, vector Y and matrix X in programme (3.37) are made up of (i) gradients of functions $\mathcal{F}$, $\mathcal{Z}$, $\mathcal{T}$, $\mathcal{K}$, and $\mathcal{L}$, which are evaluated using data available at the status-quo and (ii) the fixed vector I.[26] The Lagrangian of problem (3.37) can be written as

$$L = Y^\top \dot{\nu} - \beta^\top [X^\top \dot{\nu} - \hat{\rho}] - \gamma[\dot{\nu}^\top \dot{\nu} - 1], \tag{3.38}$$

where

$$\beta^\top = \begin{bmatrix} \beta_1 & \dots & \beta_{4+m} \end{bmatrix}, \qquad m = 0 \text{ or } m = 1$$

is the vector of Lagrange multipliers on the $4 + m$ constraints $X^\top \dot{\nu} \leq \hat{\rho}$ and $\gamma \in \mathbf{R}$ is the Lagrange multiplier on the constraint $\dot{\nu}^\top \dot{\nu} \leq 1$.

Let the mappings of the solution and the associated Lagrange multipliers at the optimum of problem (3.37), when $\dot{z} = 0$, be given by $\dot{\nu}_X : \mathbf{R}^{26} \longmapsto \mathbf{R}^{13}$, $\beta_X : \mathbf{R}^{26} \longmapsto \mathbf{R}^m$, and $\gamma_X : \mathbf{R}^{26} \longmapsto \mathbf{R}$ with image[27]

$$\langle \dot{\nu}^*,\ \beta^*,\ \gamma^* \rangle \ \in \ \Big\langle \dot{\nu}_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\quad \beta_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \Big\rangle.$$

We focus on the special case where there is no change in the emission cap at the status-quo, *i.e.,* $\dot{z} = 0$.[28] In this case, the Kuhn-Tucker first-order conditions evaluated at the optimum are[29]

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[26] Hence, their elements are given constants. Thus, X is a constant matrix and Y is a constant column vector.

[27] These mappings are set-valued and allow for multiple solutions to problem (3.37).

[28] Then $\hat{\rho} = 0_4$ if $m = 0$ and $\hat{\rho} = 0_5$ if $m = 1$. The study of the case $\dot{z} = 0$ is helpful, as we will see in Section 7, in deriving a measure of marginal abatement cost in the policy reform framework. The optimal reform that solves problem (3.37) when $\dot{z} = 0$ is an appealing reform as it is a feasible, emission non-increasing, and final consumption-increasing reform.

[29] Under the maintained Assumption 1, these conditions are both necessary and sufficient for an optimum of problem (3.37) when $\dot{z} = 0$.

$$Y - X\beta - 2\gamma\dot{\nu} = 0_{13}$$

$$X^\top\dot{\nu} \leq 0_{4+m}, \quad \beta \geq 0_{4+m}, \quad \beta_i X_i^\top \dot{\nu} = 0 \,\forall\, i = 1, \ \ldots \ , 4+m$$

$$\dot{\nu}^\top\dot{\nu} \leq 1, \quad \gamma \geq 0, \quad \gamma[\dot{\nu}^\top\dot{\nu} - 1] = 0. \tag{3.39}$$

Consider a solution to problem (3.37) with $\dot{z} = 0$

$$u^* = \langle \dot{\nu}^*, \ \beta^*, \ \gamma^* \rangle \in \langle \dot{\nu}_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right), \ \beta_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right), \ \gamma_X \left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \Big|_{\dot{z}=0}.$$

At u^*, it is possible that some of the constraints of the problem (3.37) are non-binding.[30] To characterise the solution u^* to problem (3.37) with $\dot{z} = 0$ rigorously, we would like to differentiate between constraints that are binding and those that are not at a solution to this problem. For this purpose, define an index set $\mathcal{J} = \{1, 2, \ \ldots \ , 4+m\}$. This corresponds to the $4+m$ indices of the elements of the vector of Lagrange multipliers $\beta^* = \langle \beta_1^*, \ldots, \beta_{4+m}^* \rangle$.

Since u^* is a solution to problem (3.37) with $\dot{z} = 0$, it solves the KT conditions in (3.39). We know that, in the case of binding constraints, the corresponding Lagrange multipliers take positive values. Gather the indices of all positive elements of vector β^* to form a set J. Then $J \subseteq \mathcal{J}$ and $\beta_j^* > 0$ and $X_j^\top \dot{\nu}^* = 0$ for all $j \in J$.

Since $\beta^* \geq 0_{4+m}$, the complement of set J in $\mathcal{J}$, denoted by J^c, is the set of indices of elements of β^* which are zero. Thus, for every index $j \in J^c$, the j^{th} constraint $X_j^\top \dot{\nu}^* \leq 0$ is non-binding and $\beta_j^* = 0$.

With a slight abuse of notation let the cardinalities of (or the number of elements in) sets J and J^c be also denoted by J and J^c, resp. Let the elements of J arranged in ascending order be $w_1, \ldots, w_J$. Let the elements of J^c arranged in ascending order be $o_1, \ldots, o_{J^c}$

Now we partition the vector of Lagrange multipliers β^* into β^J and β^{J^c} such that $\beta^J = \langle \beta_{w_1}^J, \ldots, \beta_{w_J}^J \rangle = \langle \beta_{w_1}^*, \ldots, \beta_{w_J}^* \rangle$ and $\beta^{J^c} = \langle \beta_{o_1}^J, \ldots, \beta_{o_{J^c}}^J \rangle = \langle \beta_{o_1}^*, \ldots, \beta_{o_{J^c}}^* \rangle$. Thus,

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[30] For example, the solution may require the optimal reform $\dot{\nu}^*$ to result in a strict differential decrease in emission, *i.e.*, it is possible that the constraint $\nabla_\nu^\top \mathcal{Z} \dot{\nu}^* \leq 0$ holds as $\nabla_\nu^\top \mathcal{Z} \dot{\nu}^* < 0$.

β^J is the vector of Lagrange multipliers of those constraints in $X^{\top}\dot{\nu} \leq 0_{4+m}$ that are binding at the optimum local riap ν^*. On the other hand, $\beta^{J^c} = 0_{J^c}$ as, by construction, $\beta_j^{J^c} = \beta_j^* = 0$ for all $j \in J^c$. Thus, β^{J^c} is the vector of Lagrange multipliers of those constraints in $X^{\top}\dot{\nu} \leq 0_{4+m}$ that are non-binding at the optimum local riap ν^*.

Similarly, matrix X can be partitioned into X^J and X^{J^c}, where matrix $X^J = \begin{bmatrix} X_{w_1} & \dots & X_{w_J} \end{bmatrix}$ corresponds to those columns of matric X which lead to constraints that are binding at the optimum (*i.e.,* ${X^J}^{\top}\dot{\nu}^* = 0$) and $X^{J^c} = \begin{bmatrix} X_{o_1} & \dots & X_{o_{J^c}} \end{bmatrix}$ corresponds to those columns of matrix X which lead to constraints that are non-binding at the optimum.[31]

Lemma 2 characterises a solution to problem (3.37) with $\dot{z} = 0$. Part (1) of Lemma 2 provides the formula for computing the Lagrange multipliers of those linear constraints of problem (3.37) that are binding at the solution, *i.e.,* it provides the formula to compute vector β^J using data available at the status-quo.

Part (2) describes the case where the optimal riap is non-zero. Hence, this riap will be final consumption-increasing, feasible, emission non-increasing, and will also satisfy the additional constraint (3.27) whenever it is present in problem (3.37) when $\dot{z} = 0$. It computes the optimal riap $\dot{\nu}^*$. This case is characterised by the Lagrange multiplier of the constraint $\dot{\nu}^{\top}\dot{\nu} \leq 1$ taking a non-zero value at the optimum, *i.e.,* $\gamma^* > 0$. Most importantly, this implies that the optimal riap has a magnitude equal to one (*i.e.,* $\dot{\nu}^* \cdot \dot{\nu}^* = 1$).

Part (3) describes the conditions under which the optimal riap is a zero vector. Intuitively, this is true when all resources (inputs) are allocated efficiently at status-quo s, so that there is no feasible reallocation that can increase final expenditure without increasing the emission level, while also respecting the any other constraint of the problem if present. In this case, the Lagrange multiplier of the constraint $\dot{\nu}^{\top}\dot{\nu} \leq 1$ is zero at the optimum, *i.e.,* $\gamma^* = 0$. This case is characterised by vector Y being a positive linear combination of columns of matrix X^J (*i.e.,* $Y = X^J\beta^J = \sum_{w_j \in J} X^J_{w_j}\beta^J_{w_j}$).

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[31] For example, if $m = 1$ and index set of binding linear constraints is $J = \{1, 3, 5\}$ then the index set of non-binding linear constraints is $J^c = \{2, 4\}$. We can partition vector β^* into $\beta^J = \langle \beta_1^*, \beta_3^*, \beta_5^* \rangle$ and $\beta^{J^c} = \langle \beta_2^*, \beta_4^* \rangle = 0_2$. $X^J = \begin{bmatrix} X_1 & X_3 & X_5 \end{bmatrix}$ and $X^{J^c} = \begin{bmatrix} X_2 & X_4 \end{bmatrix}$.

Lemma 2 *Suppose* $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ *is a tight status-quo. Let*

$$u^* = \langle \dot{\nu}^*,\ \beta^*,\ \gamma^* \rangle \in \langle \dot{\nu}_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \beta_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \Big|_{\dot{z}=0}$$

be a solution of problem (3.37) with $\dot{z} = 0$*. Consider the partition of* β^* *into* $\beta^J \in \mathbf{R}^J_{++}$ *and* $\beta^{J^c} = 0_{J^c}$*. Then the following are true:*

(1) $\dot{\nu}^*$ *is in the null-space of* ${X^J}^\top$ *and*[32]

$$\beta^J = \left({X^J}^\top X^J\right)^{-1} {X^J}^\top Y.$$

(2) $\quad Y \neq X^J \beta^J \quad \Longrightarrow \quad \gamma^* = \frac{\sqrt{(Y - X^J\beta^J)^\top (Y - X^J\beta^J)}}{2}, \quad \dot{\nu}^* = \frac{Y - X^J\beta^J}{2\gamma^*}, \quad$ *and* $\quad \dot{\nu}^* \cdot \dot{\nu}^* = 1.$

(3) $\quad$ *(i)* $\gamma^* = 0 \quad \Longleftrightarrow \quad Y = X^J\beta^J = X\beta^*$

(ii) $\gamma^* = 0 \quad \Longrightarrow \quad Y^\top \dot{\nu}^* = 0$ *and* $0_{13} \in \dot{\nu}_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right)\Big|_{\dot{z}=0}.$

Proof. The partitioning of vector β^* into β^J and β^{J^c} follows from the definitions of β^J and β^{J^c}.

(1) From the second set of conditions in (3.39) and the definition of X^J and J^c it follows that ${X^J}^\top \dot{\nu}^* = 0_{13}$ and $\beta^*_j = 0$ for all $j \in J^c$. The former implies that $\dot{\nu}^*$ is in the null-space of X^J and the latter, together with the first set of conditions in (3.39), implies that

$$Y - X\beta^* = Y - X^J\beta^J = 2\gamma^*\dot{\nu}^*. \tag{3.40}$$

Pre-multiply both sides of (3.40) with ${X^J}^\top$ to obtain

$${X^J}^\top Y - {X^J}^\top X^J \beta^J = 2\gamma^* {X^J}^\top \dot{\nu}^*. \tag{3.41}$$

The construction of set J implies that ${X^J}^\top \dot{\nu}^* = 0_J$. Hence,

$${X^J}^\top Y - {X^J}^\top X^J \beta^J = 0_J. \tag{3.42}$$

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[32] The null-space of ${X^J}^\top$ is the set: $\{\dot{\nu} \in \mathbf{R}^{13} \mid {X^J}^\top \dot{\nu} = 0_J\}$. Since, matrix X^J consists of those columns of matrix X, which lead to constraints that are binding at the optimum of problem (3.37), we have ${X^J}^\top \dot{\nu}^* = 0_J$.

This implies

$$\beta^J = \left(X^{J^\top} X^J\right)^{-1} X^{J^\top} Y.$$

(2) If $Y - X^J \beta^J \neq 0_{13}$, then the first set of conditions in (3.39) imply that $\gamma^* \dot{\nu}^* \neq 0$. Hence, $\gamma^* \neq 0$. In particular, in this case, it follows from the third set of conditions in (3.39) that $\gamma^* > 0$. Hence, the third set of conditions in (3.39) imply also that $\dot{\nu}^* \cdot \dot{\nu}^* = 1$. (3.40) implies

$$\dot{\nu}^* = \frac{Y - X^J \beta^J}{2\gamma^*} \implies \dot{\nu}^* \cdot \dot{\nu}^* = \frac{\left(Y - X^J \beta^J\right)^\top \left(Y - X^J \beta^J\right)}{4\gamma^{*2}} = 1$$

$$\implies \quad \gamma^* = \frac{\sqrt{\left(Y - X^J \beta^J\right)^\top \left(Y - X^J \beta^J\right)}}{2}.$$

(3) (i) Proof of $\implies$ is obvious from (3.40). Suppose $Y = X\beta^* = X^J \beta^J$. Then (3.40) implies that

$$\gamma^* \dot{\nu}^* = 0 \tag{3.43}$$

Suppose $\gamma^* > 0$. Then the third set of conditions imply that $\dot{\nu}^* \cdot \dot{\nu}^* = 1$. Hence, $\dot{\nu}^* \neq 0_{13}$. This implies $\gamma^* \dot{\nu}^* \neq 0$, which is a contradiction to (3.43). Hence, $\gamma^* = 0$. (ii) Since $X^{J^\top} \dot{\nu}^* = 0_J$ and $Y^\top = \beta^{J^\top} X^{J^\top}$, we have $Y^\top \dot{\nu}^* = 0$. Hence, $\dot{\nu}^*$ can be chosen as 0_{13} as, together with β^* and γ^*, it satisfies all conditions in (3.39).

Lemma 2 provides an empirical test of whether the status-quo permits final consumption-increasing and emission non-increasing riaps by checking whether the conditions indicated by Lemma 1 hold.[33] In particular, condition (3.36) in Lemma 1 holds if and only if the solution to problem (3.37) with $\dot{z} = 0$ is such that γ^* is equal to zero. For in that case, as indicated by (i) of part 3 of Lemma 2, the gradient of the objective function of problem (3.37), which is vector $Y = \nabla_\nu \mathcal{F}(\bar{\nu})$, is a non-negative linear combination of the columns of matrix X (as defined in (3.28) and (3.29)): $Y = X^J \beta^J = X^J \beta^J + X^{J^c} \beta^{J^c} = X\beta^* = \sum_{j=1}^{4+m} X_j \beta_j^*$, where $\beta^* \neq 0_{4+m}$.[34] This is exactly condition (3.36) in Lemma 1.

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[33] In a follow-up research paper, we implement this test empirically, using province level data, to check for existence of such riaps in Chinese provinces.

[34] This is because if $\beta^* = 0_{4+m}$, then $Y = \nabla_\nu \mathcal{F}(\bar{\nu}) = 0_{13}$, which is a contradiction to part (i) of Assumption 1.

Lemma 3 *Suppose* $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}_{+}^{25}$ *is a tight status-quo. Let*

$$u^{*} = \langle \dot{\nu}^{*},\ \beta^{*},\ \gamma^{*} \rangle \in \langle \dot{\nu}_{X}\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \beta_{X}\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_{X}\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \Big|_{\dot{z}=0}.$$

Then, condition (3.36) in Lemma 1 holds if and only if $\gamma^{*} = 0$.

3.7 Feasible, Consumption-increasing, and Emission non-increasing Reforms and Policy-reform Based Marginal Abatement Cost (MAC)

It is possible that the current status-quo is one where the existing stocks of resources are not allocated efficiently across sectors given the current technology and economic conditions. Allocative inefficiencies could be both with respect to emission-generation and production for meeting final consumption expenditure.[35] In the presence of such inefficiencies, it is possible, in the short-run (*i.e.,* with the existing technology and economic conditions), to design feasible input reforms (by reallocating existing resources) that can increase final consumption expenditure without increasing the emission level. In this section, employing Lemma 1 presented in the previous section, we provide theoretical conditions for the existence of such reforms. Employing Lemma 2, we also develop a methodology to test, using current data, whether the status-quo permits such reforms. In the event that the status-quo permits such reforms, we provide the formula, based on currently available data, that computes the optimal feasible, final consumption-increasing, and emission non-increasing reform. We also develop a measure of marginal abatement cost based on the concept of a marginal reform in active policies.

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[35] In a follow-up chapter that applies province-level data from China to the theory developed in this work, we find that such allocative inefficiencies are rampant across all provinces in China. Using international data, Murty (2016) finds allocative inefficiencies to be prevalent across 118 countries of the world.

3.7.1 Existence of Feasible, Consumption-increasing, and Emission Non-increasing Reforms

Suppose $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ is a tight status-quo. Define a cone $\Lambda(\bar{\nu})$ formed by taking all possible non-negative linear combinations of the gradients $\nabla_\nu \mathcal{Z}$, $\nabla_\nu \mathcal{T}$, $\nabla_\nu \mathcal{K}$, and $\nabla_\nu \mathcal{L}$, evaluated at the status-quo.[36]

$$\Lambda(\bar{\nu}) = \Big\{ u \in \mathbf{R}^{13} \;\Big|\; u = \lambda_Z \nabla_\nu \mathcal{Z}(\bar{\nu}) + \lambda_T \nabla_\nu \mathcal{T}(\bar{\nu}) + \lambda_K \nabla_\nu \mathcal{K}(\bar{\nu}) + \lambda_L \nabla_\nu \mathcal{L}(\bar{\nu}), \\ \langle \lambda_Z,\, \lambda_T,\, \lambda_K,\, \lambda_L \rangle > 0_4 \Big\}.$$

Denote the interior of $\Lambda(\bar{\nu})$ as $\hat{\Lambda}(\bar{\nu})$.[37]

Lemma 1, based on the MTA, can be employed to characterise the existence of feasible, final consumption-increasing, and emission non-increasing reforms. Recall that, starting from status-quo s, a riap $\dot{\nu}$ is feasible, final expenditure increasing, and emission non-increasing if (3.33) holds.

Theorem 4 *Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ be a tight status-quo. There does not exist a riap $\dot{\nu}$ satisfying (3.33) if and only if $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \Lambda(\bar{\nu})$. Further,*

$$\nabla_\nu \mathcal{F}(\bar{\nu}) \in \Lambda(\bar{\nu}) \iff \nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu}).$$

Proof. Recalling (3.28), choose $m = 0$ so that matrix $X = \boldsymbol{\chi}$. From Lemma 1 it then follows that (3.33) holds if and only if there do not exist a scalar $\lambda_Y > 0$ and a vector $\langle \lambda_Z,\, \lambda_T,\, \lambda_K,\, \lambda_L \rangle \geq 0_4$ such that

$$\lambda_Y Y - \lambda_Z \nabla_\nu \mathcal{Z} - \lambda_T \nabla_\nu \mathcal{T} - \lambda_K \nabla_\nu \mathcal{K} - \lambda_L \nabla_\nu \mathcal{L} = 0_{13}. \tag{3.44}$$

Given that $\lambda_Y > 0$, let $\frac{1}{\lambda_Y} \langle \lambda_Z,\, \lambda_T,\, \lambda_K,\, \lambda_L \rangle = \langle \hat{\lambda}_Z,\, \hat{\lambda}_T,\, \hat{\lambda}_K,\, \hat{\lambda}_L \rangle$. Then, (3.25) and

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[36] We exclude the case where the weights on all gradients is equal to zero.

[37] The cone $\hat{\Lambda}(\bar{\nu})$ formed by taking all *positive* linear combinations of the gradients $\nabla_\nu \mathcal{Z}$, $\nabla_\nu \mathcal{T}$, $\nabla_\nu \mathcal{K}$, and $\nabla_\nu \mathcal{L}$:

$$\hat{\Lambda}(\bar{\nu}) = \Big\{ u \in \mathbf{R}^{13} \;\Big|\; u = \lambda_Z \nabla_\nu \mathcal{Z}(\bar{\nu}) + \lambda_T \nabla_\nu \mathcal{T}(\bar{\nu}) + \lambda_K \nabla_\nu \mathcal{K}(\bar{\nu}) + \lambda_L \nabla_\nu \mathcal{L}(\bar{\nu}), \\ \langle \lambda_Z,\, \lambda_T,\, \lambda_K,\, \lambda_L \rangle \gg 0_4 \Big\}.$$

(3.44) imply[38]

$$\begin{bmatrix} F_k \\ 0 \\ F_e E_k^R \\ F_l \\ 0 \\ F_e E_l^R \\ F_e \\ -p_C \\ -\xi_G \frac{\epsilon_G}{h_G} \\ \frac{\epsilon_C}{h_{NC}}[F_e - \xi_C] \\ \frac{\epsilon_G}{h_{NG}}[F_e - \xi_G] \\ F_e \frac{\epsilon_O}{h_O} - p_O \\ -[\Phi_a + \Phi_f] \end{bmatrix} = \hat{\lambda}_Z \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \alpha_C \\ \alpha_G \\ \alpha_C \\ \alpha_G \\ \alpha_O \\ -s \end{bmatrix} + \hat{\lambda}_T \begin{bmatrix} 0 \\ -E_k^C \\ 0 \\ 0 \\ -E_l^C \\ 0 \\ 1 \\ -E_x^C \\ -\frac{\epsilon_G}{h_G} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \hat{\lambda}_K \begin{bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \hat{\lambda}_L \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{3.45}$$

Clearly, $\langle \hat{\lambda}_Z, \hat{\lambda}_T, \hat{\lambda}_K, \hat{\lambda}_L \rangle \neq 0_4$, as under our maintained Assumption 1, $\nabla_\nu \mathcal{F}(\bar{\nu}) \neq 0_{13}$. Hence, $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \Lambda(\bar{\nu})$. We show that, under the maintained assumptions, $\langle \hat{\lambda}_Z, \hat{\lambda}_T, \hat{\lambda}_K, \hat{\lambda}_L \rangle \gg 0_4$. This would imply that $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu})$.

Suppose $\hat{\lambda}_Z = 0$. Then (3.45) implies $-[\Phi_a + \Phi_f] = 0$, which is in contradiction to maintained Assumption 1, part (iv). Hence, $\hat{\lambda}_Z > 0$.

Suppose $\hat{\lambda}_K = 0$. Then (3.45) implies $E_k^C = 0$, which is in contradiction to maintained Assumption 1, part (ii). Hence, $\hat{\lambda}_K > 0$.

Suppose $\hat{\lambda}_L = 0$. Then (3.45) implies $E_l^C = 0$, which is in contradiction to maintained Assumption 1, part (ii). Hence, $\hat{\lambda}_L > 0$.

Suppose $\hat{\lambda}_T = 0$. Then (3.45) implies $\hat{\lambda}_L = \hat{\lambda}_K = 0$ (see the second and fifth rows of column vectors on both sides of (3.45)), which is in contradiction to our conclusions

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[38] We omit writing the arguments of the functions below but assume throughout that they are evaluated at the status-quo.

above that $\hat{\lambda}_L > 0$ and $\hat{\lambda}_K > 0$. Hence, $\hat{\lambda}_T > 0$.

Theorem 4 shows that, unless $\nabla_\nu \mathcal{F}(\bar{\nu})$ is a positive linear combination of gradients $\nabla_\nu \mathcal{Z}$, $\nabla_\nu \mathcal{T}$, $\nabla_\nu \mathcal{K}$, and $\nabla_\nu \mathcal{L}$, there will always exist riaps at the status-quo that are feasible and final consumption-increasing, but not emission increasing.

3.7.2 Developing an Empirical Test for Existence of Feasible, Consumption-increasing, and Emission non-increasing Reforms and Computing the Optimal Marginal Reform

Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ be a tight status-quo and $\dot{z}$ be a desired reform in the emission cap. Consider the following problem, which seeks the feasible and permissible riap lying in the unit ball (*i.e.,* which takes us to policies in the local neighbourhood of size one of the status-quo policy vector $\bar{\nu}$) that leads to the greatest differential increase in the final expenditure.

$$\begin{aligned}
\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) := \max_{\dot{\nu} \in \mathbf{R}^{13}} \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot \dot{\nu} \;\equiv\; Y^\top \dot{\nu} \\
\text{subject to} \\
\nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \dot{\nu} \le \dot{z} \\
\nabla_\nu^\top \mathcal{T}(\bar{\nu}) \dot{\nu} \le 0, \quad \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \dot{\nu} \le 0, \quad \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \dot{\nu} \le 0, \\
\dot{\nu}^\top \dot{\nu} \le 1
\end{aligned} \tag{3.46}$$

It is clear that problem (3.46) is a special case of problem (3.37) with $m = 0$ and matrix $X = \boldsymbol{\chi}$. The Lagrangian of problem (3.46) can be written using (3.38) as

$$\begin{aligned}
L_0 \;=\; & \nabla_\nu^\top \mathcal{F}(\bar{\nu}) \dot{\nu} - \beta_1 [\nabla_\nu^\top \mathcal{Z}(\bar{\nu}) \dot{\nu} - \dot{z}] - \beta_2 \nabla_\nu^\top \mathcal{T}(\bar{\nu}) \dot{\nu} - \beta_3 \nabla_\nu^\top \mathcal{L}(\bar{\nu}) \dot{\nu} - \beta_4 \nabla_\nu^\top \mathcal{K}(\bar{\nu}) \dot{\nu} \\
& -\gamma [\dot{\nu}^\top \dot{\nu} - 1].
\end{aligned} \tag{3.47}$$

Suppose $\dot{z} = 0$. With matrix $X = \boldsymbol{\chi}$, Lemma 2 can be applied to compute the optimal riap using data available at the status-quo. In this case, a slightly stronger version of Lemma 3 applies: at the optimum of problem (3.46) (equivalently, problem (3.37) with $m = 0$ and matrix $X = \boldsymbol{\chi}$), γ^* is equal to zero if and only if the gradient of the objective function is a *positive* linear combination of the columns of matrix X, *i.e.,* if Y lies in the open cone $\hat{\Lambda}(\bar{\nu})$. Thus, we can test the conclusions of Theorem 4 on the existence of final consumption-increasing and emission non-increasing feasible riaps at the status-quo by checking the sign of γ^*, which is computed using Lemma 2.

Corollary 5 *Suppose* $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ *is a tight status-quo and* $X = \boldsymbol{\chi}$. *Let*

$$\langle \dot{\nu}^*,\ \beta^*,\ \gamma^* \rangle \in \langle \dot{\nu}_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \beta_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \Big|_{\dot{z}=0}.$$

Then, $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu}) \iff \gamma^* = 0.$

Proof. If $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu})$ then, since $\hat{\Lambda}(\bar{\nu})$ is an open cone, there exist $\hat{\lambda} \gg 0_4$ such that

$$\nabla_\nu \mathcal{F}(\bar{\nu}) = \hat{\lambda}_1 \nabla_\nu \mathcal{Z}(\bar{\nu}) + \hat{\lambda}_2 \nabla_\nu \mathcal{T}(\bar{\nu}) + \hat{\lambda}_3 \nabla_\nu \mathcal{K}(\bar{\nu}) + \hat{\lambda}_4 \nabla_\nu \mathcal{L}(\bar{\nu}).$$

Hence, it follows from Lemma 2 that $\beta^* = \hat{\lambda}$, $\gamma^* = 0$, and $\dot{\nu}^* = 0$ solves problem problem (3.46) (equivalently, problem (3.37) with $m = 0$ and matrix $X = \boldsymbol{\chi}$) with $\dot{z} = 0$.

If $\gamma^* = 0$, then from Lemma 2 it follows that

$$\nabla_\nu \mathcal{F}(\bar{\nu}) = \beta_1^* \nabla_\nu \mathcal{Z}(\bar{\nu}) + \beta_2^* \nabla_\nu \mathcal{T}(\bar{\nu}) + \beta_3^* \nabla_\nu \mathcal{K}(\bar{\nu}) + \beta_4^* \nabla_\nu \mathcal{L}(\bar{\nu}).$$

Proceeding along the lines of proof of Theorem 4, we can show that, in this case, $\beta_j^* > 0$ for $j = 1, \ldots, 4$. Hence, $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu})$.

3.7.3 Defining and Computing the Marginal Abatement Cost (MAC): A Policy Reform Approach

Suppose $\langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ is a tight status-quo, $X = \boldsymbol{\chi}$, and let

$$\langle \dot{\nu}^*,\ \beta^*,\ \gamma^* \rangle \in \langle \dot{\nu}_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \beta_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \Big|_{\dot{z}=0}.$$

The policy reform approach proposes a new definition of marginal abatement cost (MAC). Allowing for allocative inefficiencies at the status-quo, problem (3.46) with $\dot{z} = 0$ identifies the best feasible local riap ($\dot{\nu}^*$) that results in the maximum differential increase in final expenditure without increasing the emission level. From this we can compute the maximum increase in final expenditure made possible in problem (3.46) with $\dot{z} = 0$, which is given by[39]

$$\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0) = \nabla_\nu \mathcal{F}(\bar{\nu}) \cdot \dot{\nu}^*.$$

It follows that the best policy vector in the local neighbourhood of the status-quo is $\bar{\nu} + \dot{\nu}^*$.

It is intuitive that if the emission cap is decreased at the status-quo, *i.e.,* if $\dot{z} < 0$, then the set of local riaps that are permissible shrinks:

$$\{\dot{\nu} \in \mathbf{R}^{13}_+ \mid \nabla^\top_\nu \mathcal{Z}(\bar{\nu})\dot{\nu} \leq \dot{z}\} \subset \{\dot{\nu} \in \mathbf{R}^{13}_+ \mid \nabla^\top_\nu \mathcal{Z}(\bar{\nu})\dot{\nu} \leq 0\} \quad \text{if} \quad \dot{z} < 0.$$

Hence, the set of reforms that are feasible, permissible, and lead to increases in final expenditure shrinks when $\dot{z} < 0$ compared to the case when $\dot{z} = 0$. The problem (3.46) can compute the best local riap when $\dot{z} < 0$. The maximum increase in final expenditure made possible in the new emission regime is given by $\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z})$. It is intuitive that, because the feasible and permissible set of riaps shrinks when the emission cap reduces, we have

$$\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) \leq \mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0),$$

that is, a decrease in the emission cap at the status-quo will generally imply a reduction in the maximum potential increase in final expenditure starting from an allocatively inefficient status-quo.

In the context of policy reforms, MAC can be defined as the reduction in the maximum potential increase in final expenditure (induced by local riaps) per unit decrease in the emission cap at the status-quo:

$$\mathcal{MAC}(\Theta, \bar{\nu}, \bar{y}, \bar{z}) := \lim_{\dot{z} \longrightarrow 0} \frac{\partial \mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) - \mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0)}{\dot{z}} = \frac{\partial \mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z})}{\partial \dot{z}}\Big|_{\dot{z}=0}.$$

An application of the envelope theorem leads to the conclusion that the MAC, so defined, is given by the value of the Lagrange multiplier of the linear emission constraint in

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[39] See the value function in problem (3.46).

problem (3.46) at the optimum, namely, by β_1^*.

$$\mathcal{MAC}(\Theta, \bar{\nu}, \bar{y}, \bar{z}) := \left.\frac{\partial L_0}{\partial \dot{z}}\right|_{\dot{z}=0} = \beta_1^*, \tag{3.48}$$

where L_0 is the Lagrangian of problem (3.46), defined in (3.47). Thus, when $\dot{z} = 0$, part 1 of Lemma 2 provides the formula to compute the vector of all Lagrange multipliers β^* of problem (3.37) and hence problem (3.46) using status-quo data. Hence, if the emission constraint is binding, *i.e.,* $1 \in J$, then $\beta_1^* > 0$ (the MAC is positive). If it is non-binding, *i.e.,* $1 \in J^c$, then $\beta_1^* = 0$ (the MAC is zero).[40]

3.8 Consumption-increasing and Emission Non-increasing Reforms: Some Special Cases

Typically, if non-empty, the set of all local riaps that are feasible, final consumption-increasing, and emission non-increasing will be big with a continuum of such reforms. In Section 3.7.2, we outlined how the optimal riap in this set (*i.e.,* the local riap in this set that increases final expenditure the most) can be computed using the formulae derived in Lemma 2. In this section, we study also the existence of other interesting reform vectors that lie in this set of feasible, final consumption-increasing, and emission non-increasing riaps.

Existence of feasible, final consumption-increasing, and emission non-increasing riaps that are also associated with particular changes in other instruments of active policies such as decreases or increases in fossil-fuel based energy or increases or decreases in carbon sequestration efforts or renewable energy can be theoretically characterised and empirically tested using Lemmas 1 and 2, when matrix X is given by (3.29). An empirical analysis, to be conducted in a follow-up to this chapter, will shed more light on the detailed composition of such reforms, *e.g.,* whether such reforms involve inter-fuel substitution from emission-intensive to less emission intensive fuels.

In this section, we provide the characterisation using the MTA and empirical tests for the

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[40] Recall, J is the set of indices of all binding constraints of problem (3.37), while J^c is the set of indices of all non-binding constraints of the same problem.

existence of feasible final consumption-increasing, and emission non-increasing reforms at the status-quo that also entail particular changes in usage of other inputs such as fossil-fuel based energy, renewable energy, and afforestation. Some of these reforms may seem counter-intuitive, but in theory, as our results demonstrate, they cannot be ruled out at a status-quo with allocative inefficiencies.

3.8.1 On the Existence of Feasible, Consumption-increasing, and Emission Non-increasing Reforms Satisfying Additional Constraints on Inputs

Let $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ be a tight status-quo such that $\nabla_{\nu}\mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$. Then, it follows from Theorem 4 that there exist riaps at s that are final expenditure increasing, feasible, and result in no increase in emission. As indicated in Section 3.6.2, the optimal feasible, final consumption-increasing, and emission non-increasing reform can be computed by applying Lemma 2 with matrix $X = \boldsymbol{\chi}$.

Now suppose, within the set of feasible, final expenditure increasing, and emission non-increasing riaps, we seek riaps that satisfy an additional linear restriction on inputs.[41] In Section 3.5, we modelled an additional linear restriction on riaps by employing a 13-dimensional vector I. Given I, the additional restriction can take forms[42]

$$I^{\top}\dot{\nu} > 0 \qquad \text{or} \qquad I^{\top}\dot{\nu} < 0 \qquad \text{or} \qquad \text{neither.}$$

Employing Lemmas 1 and 2, Theorem 6, below, characterises three mutually exclusive and exhaustive cases, namely, (i) the case where *all* feasible, final consumption-increasing, and emission non-increasing riaps at the status-quo satisfy the additional restriction $I^{\top}\dot{\nu} > 0$, (ii) the case where *all* feasible, final consumption-increasing, and emission non-increasing riaps at the status-quo satisfy the additional restriction $I^{\top}\dot{\nu} < 0$, and (iii) the case where, at the status-quo, some feasible, final consumption-increasing,

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[41] For example, we may like to test for the existence of final expenditure increasing, feasible, and emission non-increasing riaps that also involve increases in afforestation.

[42] For examples of such reforms, see Sections 3.8.2 and 3.8.3.

and emission non-increasing riaps satisfy $I^\top \dot{\nu} \leq 0$ and some feasible, final consumption-increasing, and emission non-increasing riaps satisfy $I^\top \dot{\nu} \geq 0$.

For example, it may be possible that the status-quo is one that admits feasible, final consumption-increasing, and emission non-increasing riaps, but *all* such riaps imply a reduction (alternatively, *all* such riaps imply an increase) in usage of coal. Or it may be the case that some of the feasible, final consumption-increasing, and emission non-increasing riaps that exist at the status-quo imply a reduction in usage of coal, while other feasible, final consumption-increasing, and emission non-increasing riaps imply increases in the usage of coal (perhaps because they also involve decreases in other fossil fuels or increase in afforestation to counter the increase in emission due to increase in the usage of coal).[43]

To state the theorem, we first define the ray comprising of all vectors that are proportional to vector I (with positive constants of proportionality), as

$$\mathcal{I} = \{u \in \mathbf{R}^{13} \mid u = \kappa I,\ \kappa > 0\}.$$

Theorem 6 *Suppose* $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ *is a tight status-quo such that* $\nabla_\nu \mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$ *and* I *and* $\nabla_\nu \mathcal{F}(\bar{\nu})$ *are not collinear. Then the following are true at* s*:*

(i) Any final consumption-increasing, feasible, emission non-increasing riap $\dot{\nu}$ *implies* $I^\top \dot{\nu} > 0$ *if and only if* $\nabla_\nu \mathcal{F}(\bar{\nu}) \in (\Lambda(\bar{\nu}) + \mathcal{I}) \setminus \Big(\hat{\Lambda}(\bar{\nu}) \cup \mathcal{I}\Big) =: \Psi.$

(ii) Any final consumption-increasing, feasible, emission non-increasing riap (or mriap) $\dot{\nu}$ *implies* $I^\top \dot{\nu} < 0$ *if and only if* $\nabla_\nu \mathcal{F}(\bar{\nu}) \in (\Lambda(\bar{\nu}) - \mathcal{I}) \setminus \Big(\hat{\Lambda}(\bar{\nu}) \cup \mathcal{I}\Big) =: \xi.$

(iii) There exists a final consumption-increasing, feasible, emission non-increasing riap $\dot{\nu}$ *such that* $I^\top \dot{\nu} \leq 0$ *and there exists a final consumption-increasing increasing, feasible, emission non-increasing riap* $\dot{\nu}'$ *such that* $I^\top \dot{\nu}' \geq 0$ *if and only if* $\nabla_\nu \mathcal{F}(\bar{\nu}) \in (\Psi \cup \xi)^c \equiv \mathbf{R}^{13} \setminus (\Psi \cup \xi).$

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[43] Our methodology is also rich to design reforms which hold even some inputs fixed and focus on reforms in other policy variables by considering additional constraints. *e.g.*, reforms which hold capital fixed in short run and focus on reforms in energy inputs and labor, etc.

Proof. (i) Any consumption increasing, feasible, emission non-increasing riap $\dot{\nu}$ implies $I^\top \dot{\nu} > 0$ if and only if there does not exist a riap $\dot{\nu}'$ such that

$$Y^\top \dot{\nu}' > 0, \qquad -\boldsymbol{\chi}^\top \dot{\nu}' \geq 0_4, \qquad \text{and} \qquad -I^\top \dot{\nu}' \geq 0. \tag{3.49}$$

From MTA, the above is true if and only if there does not exist scalar $\lambda_Y > 0$ and a vector $\langle \lambda_Z, \lambda_T, \lambda_K, \lambda_L, \lambda_I \rangle \geq 0_5$ such that

$$Y = \hat{\lambda}_Z \nabla_\nu \mathcal{Z} + \hat{\lambda}_T \nabla_\nu \mathcal{T} + \hat{\lambda}_K \nabla_\nu \mathcal{K} + \hat{\lambda}_L \nabla_\nu \mathcal{L} + \hat{\lambda}_I \nabla_\nu \mathcal{I},$$

where $\langle \hat{\lambda}_Z,\ \hat{\lambda}_T,\ \hat{\lambda}_K,\ \hat{\lambda}_L,\ \hat{\lambda}_I \rangle = \frac{1}{\lambda_Y} \langle \lambda_Z,\ \lambda_T,\ \lambda_K,\ \lambda_L,\ \lambda_I \rangle$. Suppose $\hat{\lambda}_I = 0$, then

$$Y = \hat{\lambda}_Z \nabla_\nu \mathcal{Z} + \hat{\lambda}_T \nabla_\nu \mathcal{T} + \hat{\lambda}_K \nabla_\nu \mathcal{K} + \hat{\lambda}_L \nabla_\nu \mathcal{L},$$

But in the proof of Theorem we saw that the above is possible if and only if $\langle \hat{\lambda}_Z,\ \hat{\lambda}_T,\ \hat{\lambda}_K,\ \hat{\lambda}_L,\ \hat{\lambda}_I \rangle \gg 0_4$, that is, if and only if $Y \equiv \nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu})$, which contradicts maintained assumption of this theorem that $\nabla_\nu \mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$. Hence, $\hat{\lambda}_I > 0$. Suppose $\langle \hat{\lambda}_Z,\ \hat{\lambda}_T,\ \hat{\lambda}_K,\ \hat{\lambda}_L \rangle = 0_4$, then this implies that $Y \equiv \nabla_\nu \mathcal{F}(\bar{\nu}) = \hat{\lambda}_I I$, which contradicts maintained assumption of this theorem that I and $\nabla_\nu \mathcal{F}(\bar{\nu})$ are not collinear. Hence, $\langle \hat{\lambda}_Z,\ \hat{\lambda}_T,\ \hat{\lambda}_K,\ \hat{\lambda}_L,\ \hat{\lambda}_I \rangle > 0_5$ with $\hat{\lambda}_I \neq 0$, $\langle \hat{\lambda}_Z,\ \hat{\lambda}_T,\ \hat{\lambda}_K,\ \hat{\lambda}_L \rangle \neq 0_4$, and $Y \equiv \nabla_\nu \mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$. Hence, $Y \equiv \nabla_\nu \mathcal{F}(\bar{\nu}) \in (\Lambda(\nu) + \mathcal{I}) \setminus \left(\hat{\Lambda}(\bar{\nu}) \cup \mathcal{I} \right) =: \Psi$.

(ii) Any consumption increasing, feasible, emission non-increasing riap $\dot{\nu}$ implies $I^\top \dot{\nu} < 0$ if and only if there does not exist a riap $\dot{\nu}'$ such that

$$Y^\top \dot{\nu}' > 0, \qquad -\boldsymbol{\chi}^\top \dot{\nu}' \geq 0_4, \qquad \text{and} \qquad I^\top \dot{\nu}' \geq 0. \tag{3.50}$$

From MTA, the above is true if and only if there does not exist scalar $\lambda_Y > 0$ and a vector $\langle \lambda_Z, \lambda_T, \lambda_K, \lambda_L, \lambda_I \rangle \geq 0_5$ such that

$$Y = \hat{\lambda}_Z \nabla_\nu \mathcal{Z} + \hat{\lambda}_T \nabla_\nu \mathcal{T} + \hat{\lambda}_K \nabla_\nu \mathcal{K} + \hat{\lambda}_L \nabla_\nu \mathcal{L} - \hat{\lambda}_I \nabla_\nu \mathcal{I},$$

Conclusions follow from employing steps similar to those in the proof of part (i) of this theorem.

(iii) This follows in an obvious manner, when we realise that sets Ψ, ξ, $(\Psi \cup \xi)^c$ comprise a partition of $\mathbf{R}^{13}$, so that if $Y \in (\Psi \cup \xi)^c$, then there exists no $\dot{\nu}'$ that satisfies either (3.49) or (3.50).

Corollary 7, below, shows how conclusions of Theorem 6 can be empirically tested using data at the status-quo by employing Lemmas 1 and 2.

Corollary 7 *Suppose* $s = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ *is a tight status-quo and* $m = 1$ *so that* $X = \begin{bmatrix} \chi & X_5 \end{bmatrix}$ *in problem (3.37) with* $X_5 = I$ *or* $X_5 = -I$*. Let*

$$u^* = \langle \dot{\nu}^*,\ \beta^*,\ \gamma^* \rangle \in \langle \dot{\nu}_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \beta_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right),\ \gamma_X\left(\bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \rangle \big|_{\dot{z}=0},$$

i.e., u^* *solves the problem (3.37). Suppose* $\nabla_\nu \mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$ *and* I *and* $\nabla_\nu \mathcal{F}(\bar{\nu})$ *are not collinear. Then,*

(i) $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \Psi \iff \left[\gamma^* = 0,\ \langle \beta_1^*, \ldots, \beta_4^* \rangle \neq 0_4,\ \beta_5^* > 0\right]$, *when* $X_5 = I$.[44]

(ii) $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \xi \iff \left[\gamma^* = 0,\ \langle \beta_1^*, \ldots, \beta_4^* \rangle \neq 0_4,\ \beta_5^* > 0\right]$, *when* $X_5 = -I$.

(iii) $\nabla_\nu \mathcal{F}(\bar{\nu}) \in (\Psi \cup \xi)^c \iff \left[\gamma^* \neq 0 \text{ when } X_5 = I\right]$ *and* $\left[\gamma^* \neq 0 \text{ when } X_5 = -I\right]$.[45]

3.8.2 Fossil-fuel Energy-based Reforms

Theorem 6 and Corollary 7 can be employed to characterise and empirically test the possibility that all final consumption-increasing, emission non-increasing, and feasible reforms require a necessary reduction in usage of fossil-fuel based energy at the

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[44] That is, any final consumption-increasing, feasible, emission non-increasing riap $\dot{\nu}$ implies $I^\top \dot{\nu} > 0$ if and only if $\gamma^* = 0$, $\langle \beta_1^*, \ldots, \beta_4^* \rangle \neq 0_4$, and $\beta_5^* > 0$. The latter conditions are required because, if $\beta_5^* = 0$, then the first (first-order) condition in (3.39) together with $\gamma^* = 0$ implies $\nabla_\nu \mathcal{F}(\bar{\nu}) = \sum_{i=1}^4 \beta_i^* X_i$, *i.e.,* $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \Lambda(\bar{\nu})$. Theorem 4 then implies $\nabla_\nu \mathcal{F}(\bar{\nu}) \in \hat{\Lambda}(\bar{\nu})$, which is a contradiction to our maintained assumption that $\nabla_\nu \mathcal{F}(\bar{\nu}) \notin \hat{\Lambda}(\bar{\nu})$. If $\langle \beta_1^*, \ldots, \beta_4^* \rangle = 0_4$, then $\gamma^* = 0$ implies that $\nabla_\nu \mathcal{F}(\bar{\nu}) = \beta_5^* I$, which contradicts the maintained assumption that I and $\nabla_\nu \mathcal{F}(\bar{\nu})$ are not collinear.

[45] That is, at the status-quo, there exists a final consumption-increasing, feasible, emission non-increasing riap $\dot{\nu}$ such that $I^\top \dot{\nu} < 0$ and there exists a final expenditure increasing, feasible, emission non-increasing riap $\dot{\nu}'$ such that $I^\top \dot{\nu}' > 0$ if and only if $\gamma^* \neq 0$ when $X_5 = I$ and $\gamma^* \neq 0$ when $X_5 = -I$.

status-quo. This can be checked by testing the existence of (counter-intuitive) reforms at the status-quo that are consumption increasing, emission non-increasing, and feasible entailing, also, *increases* in fossil-fuel based energy. If no such reform exists, then all final consumption-increasing, emission non-increasing, and feasible reforms necessarily require reductions in the usage of fossil-fuel based energy. In this case, we might me interested in knowing whether, in such reforms, reductions in fossil-fuel based energy is compensated by increase in energy from renewable sources.[46] If, on the other hand, there are final consumption-increasing, emission non-increasing, and feasible reforms that also allow increases in fossil-fuel based energy, then such reforms must involve concomitant increases in carbon sequestration efforts such as afforestation to absorb the increases in emission generated by increased usage of fossil-fuels.[47]

Energy from fossil-fuels can be electrical or non-electrical. Using the definitions and notations in Section 3.2.1, energy from fossil fuels is given by function $\mathcal{E}_{FF} : \mathbf{R}^{13} \longrightarrow \mathbf{R}_+$ with image

$$\begin{aligned} \mathcal{E}_{FF}(\nu) &= e_T + e_O + e_{NC} + e_{NG} \\ &= e_T + \frac{\epsilon_O}{h_O} x_O + \frac{\epsilon_C}{h_{NC}} x_{NC} + \frac{\epsilon_G}{h_{NG}} x_{NG}. \end{aligned}$$

In this case, choose I as the gradient of function $\mathcal{E}_{FF}$ evaluated at the status-quo. Thus,

$$I^\top = \langle 0, 0, 0, 0, 0, 0, 1, 0, 0, \frac{\epsilon_C}{h_{NC}}, \frac{\epsilon_G}{h_{NG}}, \frac{\epsilon_O}{h_O}, 0 \rangle.$$

Thus, starting from a tight status-quo s, a riap $\dot{\nu} \in \mathbf{R}^{13}$ is fossil fuel based energy-increasing if it differentially increases fossil-fuel based energy, *i.e.,* if $I^\top \cdot \dot{\nu} > 0$.

Theorem 6 and Corollary 7 can now be employed to characterise and to empirically test for the existence of final consumption-increasing, feasible, emission non-increasing riaps at the status-quo that also are fossil-fuel based energy-increasing.

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[46] This will be true if energy is has some complementary with inputs such as capital and labour in production of the GDP in the non-energy sector so that reduction in fossil-fuel based energy has to be compensated by increases in other sources of energy to ensure no decrease in production of GDP in this sector.

[47] Thus, the structure of such reforms is revealed when they are actually computed by employing the formulae provided in Lemma 2 and the data prevailing at the status-quo. In a follow-up paper to this research, we study the structures of such reforms in the context of Chinese provinces.

3.8.3 Reforms Impinging on Renewable Energy Generation and Afforestation

It is possible that the nature of allocative inefficiencies at the status-quo is such that the optimal short-run reform entails reduction in renewable energy. This may be because renewable energy may be currently too costly to generate: the marginal cost of producing renewable energy may be currently far higher than the marginal benefits from it. Hence, the optimal final consumption-increasing, feasible, and emission non-increasing reform may recommend diverting resources out of renewable energy sector and into other more productive sectors in a manner that there is no net increase in emission. However, it is possible that an economic unit (such a country or a province) may not undertake this optimal reform if its long-run objective of sustainable development requires it to develop its capacities to generate renewable energy or sequester carbon. Thus, it may also like to explore if there are short-run (immediate) feasible, final consumption-increasing, and emission non-increasing reforms that, even if sub-optimal today, contribute to increasing its long-run capabilities to generate renewable energy or sequester carbon.

Theorem 6 and Corollary 7 can once again be employed to study existence of such reforms at the status-quo. To study what feasible, final consumption increasing, and emission non-increasing riaps at the status-quo imply for renewable energy, we can define the vector I as

$$I = \langle 0, 0, E_k^R, 0, 0, E_l^R, 0, 0, 0, 0, 0, 0, 0 \rangle.$$

In this case, given a riap $\dot{\nu}$, $I^\top \dot{\nu} = E_k^R \dot{k}_R + E_l^R \dot{l}_R$, evaluated at the status-quo, measures the differential change in renewable energy at the status-quo.

To study what feasible, final consumption increasing, and emission non-increasing riaps at the status-quo imply for afforestation effort, we can define the vector I as

$$I = \langle 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1 \rangle.$$

In this case, given a riap $\dot{\nu}$, $I^\top \dot{\nu} = \dot{a}$. Hence, if $\dot{\nu}$ increases afforestation at the status-quo, then $I^\top \dot{\nu} > 0$.

3.9 Conclusions

This chapter allows for economic inefficiencies in the way economic units manage their resources. Employing the Motzkin's theorem of the alternative, it provides a theoretical characterisation of the existence of inefficiencies at the status-quo of an economic unit. It develops a methodology to empirically test for these theoretical conditions using data prevailing at the status-quo. At inefficient status-quos, efficiency-improving policy reforms exist. In this chapter, efficiency-improvements take the form of resource-wise feasible, consumption-increasing, and emission non-increasing reforms. Given institutional and political rigidities, often an inefficient economic unit has to choose from among allocations in only a local neighbourhood of its status-quo for efficiency improvements. Several efficiency-improving local reforms exist at an inefficient status-quo. This chapter provides a methodology to compute the optimal efficiency-improving local reform. It also derives a measure of marginal abatement cost in the framework of local policy reforms, which can be computed using status-quo data. Finally, it provides a framework to study the composition of efficiency-improving reforms. Hypotheses about different structures of efficiency-improving reforms can be tested empirically using the methodology we develop in conjunction with the data available at the status-quo.

A key role is attributed to the energy sector in this analysis. Special features of the energy inputs are identified and several details of the energy sector are sought to be modelled. In a follow-up chapter, we study functional relations that best capture the properties of the energy inputs identified in this paper. Such production functions for the energy sector and the non-energy sector using energy as an important intermediate input are estimated. Marginal abatement costs and optimal efficiency-improving reforms are computed for Chinese provinces using these estimated production functions. The theory developed in this paper is also employed in the follow-up paper to study the structures of various efficiency-improving reforms for Chinese provinces.

Chapter 4

Designing Efficiency-improvements and Measuring Marginal Abatement Costs: A Province-level Analysis of China[1]

4.1 Introduction

Murty (2016) presents a model of production, which allows for allocative inefficiencies in the way an economic unit meets its emission target. In the presence of such inefficiencies, adopting a policy reforms framework, the paper (a) shows how efficiency-improving reforms, which simultaneously promote both the economic and the environmental objectives of the producing unit, can be designed and (b) derives a measure of marginal abatement cost (MAC) based on input policies that lie in a local neighbourhood of the status-quo input policies of the economic unit. In the case of national or sub-national economic entities, the paper argues that this measure of MAC is relevant in situations where, due to endemic institutional and political rigidities, radical changes in policy variables that lead from an inefficient status-quo to the environment-constrained global optimum of the economic unit cannot be implemented. The paper applies this methodology to construct efficiency-improving reforms (defined in that paper as producer surplus increasing and emission non-increasing reforms) and to measure MACs for a sample of 118 countries, using data available at the status-quos of these countries.

In Chapter 3, the central role played by the energy sector in both the production of the desired consumption good and in the mitigation of emission was noted, and the model in Murty (2016) is extended to incorporate a more detailed modelling of the energy sector. In this extended framework, we provided a theoretical characterisation for the existence

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[1] The work in this chapter is joint with my supervisor Professor Sushama Murty.

of allocative inefficiencies at the status-quo of a national or sub-national economic entity, and developed a methodology for empirically testing whether the identified theoretical conditions for allocative inefficiencies hold at the status-quo of the economic unit. In the presence of allocative inefficiencies, “resource-wise feasible, consumption-increasing, and emission non-increasing input reforms” (which we will also refer to as “efficiency-improving reforms”) exist at the status-quo. Chapter 3 provides formulae to compute the local feasible reform that results in the maximum increase in consumption without increasing the emission level generated at the status-quo as well as a policy-reform based measure of MAC. A theoretical characterisation as well as a methodology to empirically test various hypotheses regarding the structure and composition of resource-wise feasible, consumption-increasing, and emission non-increasing reforms was also developed in Chapter 3.

The models and theoretical analyses in Murty (2016) and Chapter 3 are developed primarily with a view towards their empirical application. Empirical work is often severely constrained by data availability. The models in Murty (2016) and Chapter 3 are hence also developed keeping in mind the nature and coverage of existing data. In particular, the model in Chapter 3 is developed to study whether there are inefficiencies in the way thirty provinces in China are generating their current levels of emissions. The aim of this chapter is to empirically apply the methodology developed in Chapter 3 to study the case of these Chinese provinces.

In the next section, we briefly review the model developed in Chapter 3 and the concept of reforms in the “levels” of policy variables defined in that chapter. We argue that various measures such as the MACs defined using reforms in the levels of policy variables are not free of the units in which policy variables are measured. Hence, we need to shift to an elasticity analogue of the model developed in Chapter 3 and define policy reforms in terms of local “proportional” changes in policy variables. We reformulate the major results of Chapter 3, namely Lemmas 1 to 3, to obtain their elasticity analogues.

Empirical application of the methodology developed in Chapter 3 requires functional specifications of the energy generating and energy using technologies in intended output production. The forms that these production functions can take depend on the properties of these technologies. In Section 4.3, we identify three features of such technologies that transcend the assumptions that are usually made on intended production technologies. We show that some of the popular production functions used in the literature such as the Cobb Douglas or the CES do not satisfy all these properties. We propose two new production functions belonging to a class called the “limitational variable elasticity of substitution (LVES)” production functions that satisfy our proposed axioms regarding energy generating and energy using technologies in intended output production.

In Section 4.4, we discuss in detail the data that we use in our empirical work and the implementation methodology. Sections 4.5 to 4.9 present various results. Section 4.5 presents the results from estimating four specifications of production functions – Cobb Douglas, CES, LVES-1, and LVES-2 – for the energy using and energy generating technologies. Section 4.6 compares elasticities of substitution at data points computed using these four functional specifications. Section 4.7 presents results from computing the MACs for all provinces and shows that these are highly sensitive to the functional forms employed to estimate the production functions. Section 4.8 presents results from testing the existence of efficiency-improving reforms for all provinces and computes the optimal efficiency-improving reform for each province for two functional forms, Cobb Douglas and LVES-1. We find that, while both functional forms show that efficiency-improving reforms exist for all provinces, the structure of the optimal reform is sensitive to the functional form employed. Section 4.9 presents results from empirical tests of five hypotheses regarding the nature of efficiency-improving reforms available for each province. We conclude in Section 4.10. Some of the tables including proof of concavity of LVES-2 production function are relegated to the Appendix.

4.2 The Model

The analyses in Murty (2016) and Chapter 3 are facilitated by the adoption of the by-production approach to modelling the technology of an emission-producing unit, developed in Murty et al. (2012); and Murty (2015b); and Murty and Russell (2016). This approach is based on the work of Frisch (1965) on production theory, whose applicability to the case of producing units generating emission was demonstrated by Førsund (2009).

The by-production approach models an emission-generating technology as a composition of two sets of production relations: (i) those that describe the relationship between inputs and outputs in sectors that produce the intended outputs of the producing unit and (ii) the laws of emission generation in nature that relate emission generation to emission-causing inputs used by the producing unit as well as the relations that describe how human efforts at abatement mitigate emission generated by the producing unit.

The analysis in Chapter 3 for (i) characterising existence of efficiency improving reforms and studying their structure, (ii) developing a methodology to empirically test for their existence at the status-quo, and (iii) computing the optimal efficiency improving reforms and the marginal abatement costs is conducted in terms of reforms in the *levels* of policy variables. Though this facilitates the exposition and the intuitive understanding of the basic concepts involved, the theoretical results so derived, when estimated, will not be independent of the units in which input variables are measured.[2]

Thus, in order to take the methodology developed in Chapter 3 to data and to obtain empirical results which are independent of the units in which inputs are measured, it is helpful to conduct the analysis in Chapter 3 in terms of *proportional changes in the policy variables* (proportional policy reforms) rather than in terms of the changes in the levels of the policy variables. Thus, in this section, we first briefly lay out the basic Chapter 3 model in the context of which policy reforms are defined, review the definition of policy reform in the levels of policy variables, and use this definition to introduce policy reforms in terms of proportionate changes in the policy variables.

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[2] This was also demonstrated in Murty (2016).

The Intended-output Producing Sector

The intended-output producing sector in Chapter 3 is divided into coal-fired thermal energy sector, the renewable energy sector, and sector $\mathcal{Y}$ that is an aggregate of all other sectors including the non-electrical energy producing sectors and the gas-fired electricity producing sector.[3] The capital and labour resources of a province are hence shared between the three sub sectors of the intended-output producing sector.

The total energy available to sector $\mathcal{Y}$ is denoted by e, which is composed of

$$e = e_T + e_R + e_O + e_{NC} + e_{NG} + e_{NM}.$$

We discuss the components of e below.

Thermal electrical energy generated from coal (e_{TC}) and gas (e_{TG}) is denoted by e_T. In particular, the production function for the coal-fired electricity generating sector is given by

$$e_{TC} = E^C(k_{TC}, l_{TC}, x_{TC}),$$

where k_{TC}, l_{TC}, and x_{TC} are the inputs of capital, labour, and coal employed by this sector and e_{TC} is its intended output of electricity. Electrical energy from gas-fired electricity generating sector is directly measured in terms of the usage of gas by this sector (x_{TG}), the energy factor of gas ϵ_G, and the heat-rate of gas-fired power plants (h_{TG}) as

$$e_{TG} = \frac{\epsilon_G}{h_{TG}} x_{TG}.$$

Thus,

$$e_T = e_{TC} + e_{TG}.$$

The production function for the renewable energy sector is given by

$$e_R = E^R(k_R, l_R),$$

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[3] As explained in Chapter 3 , data availability is the main reason for this choice of categorisation of the intended-output producing sector.

where k_R and l_R are the inputs of capital and labour employed by this sector and e_R is its intended output of electricity.

The energy from usage of oil (e_O) and non-electrical energy from coal and gas (e_{NC} and and e_{NG}, resp.) are also measured directly in terms of usage of oil, coal, and gas (x_O, x_{NC}, and x_{NG}, resp.), their energy factors (ϵ_O, ϵ_C, and ϵ_G, resp.), and the inverse of their heat rates (their efficiency conversion factors) denoted by $\varepsilon_O = 1$, ε_{NC}, and ε_{NG}, resp.[4]

$$e_O = \frac{\epsilon_O}{h_O} x_O, \qquad e_{NC} = \frac{\epsilon_C}{h_{NC}} x_{NC} = \varepsilon_{NC}\epsilon_C x_{NC}, \qquad e_{NG} = \frac{\epsilon_G}{h_{NG}} x_{NG} = \varepsilon_{NG}\epsilon_G x_{NG},$$

Net import of energy by a province is denoted by e_{NM}. In our analysis, this component of total energy e is held fixed.

The production function of sector $\mathcal{Y}$, which uses energy e as an input is given by

$$\mathcal{Y} = F\left(k_Y, l_Y, e\right),$$

where k_Y and l_Y are the capital and labour units employed by this sector. The ouput of this sector is allocated to different uses as follows:

$$\begin{aligned}\mathcal{Y} = F\left(k_Y, l_Y, e\right) &= y + \Phi(a, f + a) + \xi_{TG}\frac{\epsilon_G}{h_{TG}} x_{TG} + \xi_{NC}\frac{\epsilon_C}{h_{NC}} x_{NC} + \xi_{NG}\frac{\epsilon_G}{h_{NG}} x_{NG} \\ &\quad + p_C x_{TC} + p_O x_O.\end{aligned}$$

Output created by sector $\mathcal{Y}$ finances (i) the final consumption requirements y, (ii) the forest-related expenditures of the government $\Phi(a, f + a)$, which are functions of the stock of forests f and planned annual level of afforestation actitivity a, and (iii) the costs of generating gas-powered electricity, non-electrical energy from coal and gas, and the fuel costs of coal-fired plants and of oil in the non-stationary energy sector, where ξ_G, ξ_{NC}, and ξ_{NG} denote the per-unit (levelised) costs of generating gas-fired electricity and non-electrical energy from coal and gas, resp., and p_O and p_C are the prices of physical units of oil and coal, resp.

We assume that the economic objective of a province is to increase final consumption

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[4] As explained in Chapter 3 , in the absence of data on heat rate or efficiency conversion factor for oil, full efficiency for oil is assumed. Data on heat rates for non-electrical energy from coal and gas is not directly available, while that on efficiency conversion factors can be inferred from some works. See also Section 4.4 of this paper on the description of data for more details.

expenditure y.

The Emission Generating Mechanism of Nature

Nature's emission generating mechanism is assumed to be linear. The net emission generated z_n is the difference between the gross emission generated by usage of fossil fuels and the extent of carbon sequestration due to afforestation:

$$z_n = \alpha_C[x_{TC} + x_{NC}] + \alpha_G[x_{TG} + x_{NG}] + \alpha_O x_O - sa,$$

where α_C, α_G, and α_O are the emission factors of fossil-fuels coal, gas, and oil, resp., and s is the amount of carbon sequestered by a unit of afforestation.

4.2.1 The Model in Elasticity Form

The empirical application of the theory developed in Chapter 3 is conducted in this paper in an elasticity analogue of the framework developed in Chapter 3 with policy reforms taking the form of proportional changes in the policy variables. This is because, the measure of MACs derived in Chapter 3 is not independent of the units in which the active policy variables are measured.

A vector of proportional changes in active policies starting from the tight status-quo $\bar{S} = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ is denoted by

$$q = \langle q_{k_Y}, q_{k_C}, q_{k_R}, q_{l_Y}, q_{l_C}, q_{l_R}, q_{e_T}, q_{x_{TC}}, q_{x_{TG}}, q_{x_{NC}}, q_{x_{NG}}, q_{x_O}, q_a \rangle \in \mathbf{R}^{13}.$$

Following the tradition of local policy reforms, we will be interested in small proportional changes in policy variables. A vector of proportional changes in active policies q is a vector of *local proportional changes in active policies (lpcap)* if the magnitude of this reform is less than or equal to one ($\|q\| \leq 1$).[5] Given an lpcap $q \in \mathbf{R}^{13}$, we can derive the policy reform in the levels of active policy variables (or changes in the levels of the policy variables) underlying q as the vector $\dot{\nu} = \langle \dot{k}_Y, \dot{k}_C, \dot{k}_R, \dot{l}_Y, \dot{l}_C, \dot{l}_R, \dot{e}_T, \dot{x}_{TC}, \dot{x}_{TG}, \dot{x}_{NC}, \dot{x}_{NG}, \dot{x}_O, \dot{a} \rangle$

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[5] Given a vector $a \in \mathbf{R}^n$, its length is denoted by $\|a\| := \sqrt{\sum_{i=1}^{n} a_i^2}$.

that solves

$$\begin{aligned} q &= \left\langle \frac{\dot{k}_Y}{\bar{k}_Y}, \frac{\dot{k}_C}{\bar{k}_C}, \frac{\dot{k}_R}{\bar{k}_R}, \frac{\dot{l}_Y}{\bar{l}_Y}, \frac{\dot{l}_C}{\bar{l}_C}, \frac{\dot{l}_R}{\bar{l}_R}, \frac{\dot{e}_T}{\bar{e}_T}, \frac{\dot{x}_{TC}}{\bar{x}_{TC}}, \frac{\dot{x}_{TG}}{\bar{x}_{TG}}, \frac{\dot{x}_{NC}}{\bar{x}_{NC}}, \frac{\dot{x}_{NG}}{\bar{x}_{NG}}, \frac{\dot{x}_O}{\bar{x}_O}, \frac{\dot{a}}{\bar{a}} \right\rangle \in \mathbf{R}^{13} \qquad (4.1) \\ \iff \dot{\nu} &= \Big\langle q_{k_Y}\bar{k}_Y,\ q_{k_{TC}}\bar{k}_{TC},\ q_{k_R}\bar{k}_R,\ q_{l_Y}\bar{l}_Y,\ q_{l_{TC}}\bar{l}_{TC},\ q_{l_R}\bar{l}_R,\ q_{e_T}\bar{e}_T,\ q_{x_{TC}}\bar{x}_{TC},\ q_{x_{TG}}\bar{x}_{TG}, \\ &\qquad q_{x_{NC}}\bar{x}_{NC},\ q_{x_{NG}}\bar{x}_{NG},\ q_{x_O}\bar{x}_O,\ q_a\bar{a}\Big\rangle. \end{aligned}$$

For $j = \mathcal{F},\ \mathcal{Z},\ \mathcal{T},\ \mathcal{K},\ \mathcal{L}$, define the vector

$$\eta^j = \langle \eta^j_{k_Y},\ \eta^j_{k_{TC}},\ \eta^j_{k_R},\ \eta^j_{l_Y},\ \eta^j_{l_{TC}},\ \eta^j_{l_R},\ \eta^j_{e_T},\ \eta^j_{x_{TC}},\ \eta^j_{x_{TG}},\ \eta^j_{x_{NC}},\ \eta^j_{x_{NG}},\ \eta^j_{x_O},\ \eta^j_a \rangle,$$

where given active policy variable $i = k_Y, k_C, k_R, l_Y, l_C, l_R, e_T, x_{TC}, x_{TG}, x_{NC}, x_{NG}, x_O, a$,

$$\eta^{\mathcal{F}}_i = \frac{\partial \mathcal{F}}{\partial i}\frac{\bar{i}}{\bar{y}}, \qquad \eta^{\mathcal{Z}}_i = \frac{\partial \mathcal{Z}}{\partial i}\frac{\bar{i}}{\bar{z}}, \qquad \eta^{\mathcal{T}}_i = \frac{\partial \mathcal{T}}{\partial i}\frac{\bar{i}}{\bar{e}_T}, \qquad \eta^{\mathcal{K}}_i = \frac{\partial \mathcal{K}}{\partial i}\frac{\bar{i}}{k}, \qquad \eta^{\mathcal{L}}_i = \frac{\partial \mathcal{L}}{\partial i}\frac{\bar{i}}{l}.$$

Thus, for $j = \mathcal{F}$ and $\mathcal{Z}$, η^j_i is the elasticity of function j with respect to active policy variable i evaluated at the status-quo. For $i \neq e_T$, $\eta^{\mathcal{T}}_i$ is the elasticity of function E^C with respect to policy variable i evaluated at the status-quo, while $\eta^{\mathcal{T}}_{e_T} = 1$. Intuitively, $\eta^{\mathcal{K}}_i$ (resp., $\eta^{\mathcal{L}}_i$) is the percentage increase in the demand for capital (resp., labour) due to a one-percent increase in active policy variable i evaluated at the status-quo.[6]

Employing the definitions of functions $\mathcal{F},\ \mathcal{Z},\ \mathcal{T},\ \mathcal{K},\ \mathcal{L}$, the vectors of elasticity of these functions evaluated at tight status-quo $\bar{S} = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ can be computed as[7]

$$\begin{aligned} \eta^{\mathcal{F}} &= \Big\langle \frac{F_k\bar{k}_Y}{\bar{y}},\ 0,\ \frac{F_eE^R_k\bar{k}_R}{\bar{y}},\ \frac{F_l\bar{l}_Y}{\bar{y}},\ 0,\ \frac{F_eE^R_l\bar{l}_R}{\bar{y}},\ \frac{F_e\bar{e}_T}{\bar{y}},\ \frac{-p_C\bar{x}_{TC}}{\bar{y}},\ -\xi_G\frac{\epsilon_G}{h_G}\frac{\bar{x}_{TG}}{\bar{y}}, \\ &\qquad (F_e-\xi_C)\varepsilon_{NC}\frac{\epsilon_C\bar{x}_{NC}}{\bar{y}},\ (F_e-\xi_G)\varepsilon_{NG}\frac{\epsilon_G\bar{x}_{NG}}{\bar{y}},\ \frac{(F_e\epsilon_O-p_O)\bar{x}_O}{\bar{y}},\ \frac{-[\Phi_a+\Phi_f]\bar{a}}{\bar{y}}\Big\rangle \\ \eta^{\mathcal{Z}} &= \left\langle 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ \frac{\alpha_C\bar{x}_{TC}}{\bar{z}},\ \frac{\alpha_G\bar{x}_{TG}}{\bar{z}},\ \frac{\alpha_C\bar{x}_{NC}}{\bar{z}},\ \frac{\alpha_G\bar{x}_{NG}}{\bar{z}},\ \frac{\alpha_O\bar{x}_O}{\bar{z}},\ \frac{-s\bar{a}}{\bar{z}} \right\rangle \qquad (4.2) \\ \eta^{\mathcal{T}} &= \left\langle 0,\ \frac{-E^C_k\bar{k}_{TC}}{\bar{e}_T},\ 0,\ 0,\ \frac{-E^C_l\bar{l}_{TC}}{\bar{e}_T},\ 0,\ 1,\ \frac{-E^C_x\bar{x}_{TC}}{\bar{e}_T},\ -\frac{\epsilon_G}{h_G}\frac{\bar{x}_{TG}}{\bar{e}_T},\ 0,\ 0,\ 0,\ 0 \right\rangle \\ \eta^{\mathcal{K}} &= \left\langle \frac{\bar{k}_Y}{k},\ \frac{\bar{k}_{TC}}{k},\ \frac{\bar{k}_R}{k},\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0 \right\rangle \\ \eta^{\mathcal{L}} &= \left\langle 0,\ 0,\ 0,\ \frac{\bar{l}_Y}{l},\ \frac{\bar{l}_{TC}}{l},\ \frac{\bar{l}_R}{l},\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0 \right\rangle \end{aligned}$$

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[6] In what follows, with an abuse of notation, we will call η^j_i as the elasticity of function j with respect to policy variable i evaluated at the status-quo $\bar{S}$.

[7] In the computation below, we have assumed the heat rate of oil h_O to be equal to one. Also, data on heat rates h_{NC} and h_{NG} are not directly available. Rather, we can infer estimates of efficiency conversion factors (the inverse of heat rates of coal and gas in the non-electric coal and gas sectors), denoted by ε_{NC} and ε_{NC}, resp., from some works such as the REMIND Integrated Assessment Model (Luderer et al., 2015). See Section 4.4 of this chapter.

Starting from the tight status-quo $\bar{S} = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$, the proportional changes in final consumption expenditure, net emission generation, and excess demands for thermal energy, capital, and labour induced by an lpcap q are given (using the definition of an elasticity of a function with respect to its various arguments) by[8]

$$\frac{\dot{y}}{\bar{y}} := \eta^{\mathcal{F}} \cdot q, \qquad \frac{\dot{z}_n}{\bar{z}} := \eta^{\mathcal{Z}} \cdot q, \qquad \frac{\dot{\mathcal{T}}}{\bar{e}_T} := \eta^{\mathcal{T}} \cdot q \qquad \frac{\dot{\mathcal{K}}}{k} := \eta^{\mathcal{K}} \cdot q, \qquad \frac{\dot{\mathcal{L}}}{l} := \eta^{\mathcal{L}} \cdot q \tag{4.3}$$

We say that an lpcap q is feasible at the status-quo $\bar{S}$ if it leads to no proportional increase in the excess demands for thermal energy, capital, and labour inputs, *i.e.,* if it satisfies

$$\frac{\dot{\mathcal{T}}}{\bar{e}_T} \equiv \eta^{\mathcal{T}} \cdot q \leq 0, \quad \frac{\dot{\mathcal{K}}}{k} \equiv \eta^{\mathcal{K}} \cdot q \leq 0, \quad \frac{\dot{\mathcal{L}}}{l} \equiv \eta^{\mathcal{L}} \cdot q \leq 0 \tag{4.4}$$

It leads to a proportional increase in amount available for final consumption expenditure if

$$\frac{\dot{y}}{\bar{y}} \equiv \eta^{\mathcal{F}} \cdot q > 0. \tag{4.5}$$

Given a proportional change in the emission cap $\frac{\dot{z}}{\bar{z}}$, lpcap q is permissible if

$$\frac{\dot{z}_n}{\bar{z}} \equiv \eta^{\mathcal{Z}} \cdot q \leq \frac{\dot{z}}{\bar{z}} \tag{4.6}$$

It does not lead to a proportional increase in emission if

$$\frac{\dot{z}_n}{\bar{z}} \equiv \eta^{\mathcal{Z}} \cdot q \leq 0. \tag{4.7}$$

Given an lpcap q, the change in the *levels* of policy variables it induces is given by the vector $\dot{\nu} \in \mathbf{R}^{13}$ that solves (4.1). Using this vector, we can compute the changes in the levels of final consumption, net emission generation, and all excess demands induced by q from (4.4), (4.5), and (4.7) as

$$\begin{aligned}
\dot{y} &= \bar{y}\, \eta^{\mathcal{F}} \cdot q = \nabla_{\nu} \mathcal{F}(\bar{\nu}) \cdot \dot{\nu}, \\
\dot{z}_n &= \bar{z}\, \eta^{\mathcal{Z}} \cdot q = \nabla_{\nu} \mathcal{Z}(\bar{\nu}) \cdot \dot{\nu}, \\
\dot{\mathcal{T}} &= \bar{e}_T\, \eta^{\mathcal{T}} \cdot q = \nabla_{\nu} \mathcal{T}(\bar{\nu}) \cdot \dot{\nu}, \\
\dot{\mathcal{K}} &= k\, \eta^{\mathcal{K}} \cdot q = \nabla_{\nu} \mathcal{K}(\bar{\nu}) \cdot \dot{\nu}, \\
\dot{\mathcal{L}} &= l\, \eta^{\mathcal{L}} \cdot q = \nabla_{\nu} \mathcal{L}(\bar{\nu}) \cdot \dot{\nu}.
\end{aligned} \tag{4.8}$$

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[8] Note, at a tight status-quo, the net emission generated is exactly equal to the emission cap, *i.e.,* $\bar{z}_n \equiv \mathcal{Z}(\bar{\nu}) = \bar{z}$. Hence, $\frac{\dot{z}_n}{\bar{z}}$ denotes the proportional change in net emission generation at the status-quo.

It is clear that if q is a feasible lpcap that does not lead to a proportional increase in emission and leads to a proportional increase in the amount available for final consumption expenditure, then (using terminology in Chapter 3) $\dot{\nu}$ is a feasible reform in the levels of active policy that is also emission non-increasing and final consumption increasing, *i.e.,*

$$\nabla_\nu \mathcal{T}(\bar{\nu})\cdot\dot{\nu} \leq 0, \qquad \nabla_\nu \mathcal{K}(\bar{\nu})\cdot\dot{\nu} \leq 0, \qquad \nabla_\nu \mathcal{L}(\bar{\nu})\cdot\dot{\nu} \leq 0, \qquad \nabla_\nu \mathcal{Z}(\bar{\nu})\cdot\dot{\nu} \leq 0 \qquad \nabla_\nu \mathcal{F}(\bar{\nu})\cdot\dot{\nu} > 0.$$

In addition to feasibility, increases in final consumption expenditure, and environmental permissibility, Chapter 3 also explores if a policy reform vector possibly satisfies additional constraints. Let vector I^η be the elasticity analogue of vector I in Chapter 3 that defines another linear constraint that the reform vector in levels of policy variables is required to satisfy. Then, depending on the additional constraint on the reform vector in the levels of the policy variable, the additional constraints imposed on lpcap q take the following elasticity form [9]

$$I \cdot \dot{\nu} \leq 0 \implies I^\eta \cdot q \leq 0 \qquad \text{or} \qquad I \cdot \dot{\nu} < 0 \implies I^\eta \cdot q < 0. \tag{4.9}$$

Redefine the 13×4-dimensional matrix $\boldsymbol{\chi}$ in Chapter 3 as

$$\boldsymbol{\chi} = \begin{bmatrix} \eta^{\mathcal{Z}} & \eta^{\mathcal{T}} & \eta^{\mathcal{K}} & \eta^{\mathcal{L}} \end{bmatrix}.$$

Thus, $\boldsymbol{\chi}$ is now a matrix of elasticities of functions $\mathcal{Z}$, $\mathcal{T}$, $\mathcal{K}$, and $\mathcal{L}$, rather than of their gradients as defined in Chapter 3 .

For $m = 0, 1$, redefine the $13 \times (4 + m)$-dimensional matrix X in Chapter 3 as

$$\begin{aligned} X &= \boldsymbol{\chi} && \text{if} \quad m = 0 \quad \text{and} \\ &= \begin{bmatrix} \boldsymbol{\chi} & I^\eta \end{bmatrix} && \text{if} \quad m = 1 \end{aligned} \tag{4.10}$$

and redefine vector Y in Chapter 3 as

$$Y = \eta^Y \tag{4.11}$$

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[9] For example, if we want to explore whether a policy reform in the levels of policy variable $\dot{\nu} \in \mathbf{R}^{13}$ results in an increase in thermal energy, then I is a vector with one as its seventh element and all other elements equal to zero, as then $I \cdot \dot{\nu} = \dot{e}_T$ and we can test if $I \cdot \dot{\nu} = \dot{e}_T > 0$. The elasticity analogue of this constraint requires $I^\eta = I$ so that we can test whether an lpcap q results in a proportionate increase in thermal energy by testing the constraint $I^\eta \cdot q = \frac{\dot{e}_T}{\bar{e}_T} > 0$.

Thus, in this paper, X is a matrix and Y is a vector of elasticities of various functions, rather than their gradients as defined in Chapter 3 .

4.2.2 The Elasticity Analogues of Lemmas 1 to 3 in Chapter 3

Loaded with this redefinition of matrix X and vector Y in Chapter 3 , we formulate the elasticity analogues of the three important general results in Chapter 3 .

Remark 8 *The elasticity analogue of Lemma 1 in Chapter 3 provides a theoretical characterisation of the existence of lpcap q at the status-quo satisfying*

$$\begin{aligned} Y^\top q &> 0 \\ -X^\top q &\geq 0_{4+m}. \end{aligned} \tag{4.12}$$

It is obtained by redefining X and Y in Chapter 3 using (4.10) and (4.11) and by replacing the policy reform vector in levels of policy variable $\dot{\nu}$ in Lemma 1 of Chapter 3 by lpcap q as the non-existence of a scalar $\lambda_Y > 0$ and a vector $\langle \lambda_1,\ \lambda_2, \ldots, \lambda_{4+m} \rangle \geq 0_{4+m}$ such that

$$\lambda_Y Y - \sum_{i=1}^{4+m} \lambda_i X_i = 0_{13}, \tag{4.13}$$

The empirical test for the existence of lpcaps at the status-quo that solve (4.12) requires solving the elasticity analogue of problem (3.37) in Chapter 3 . Given a proportionate increase $\frac{\dot{z}}{\bar{z}}$ in the emission cap, this problem searches for a feasible and permissible lpcap that increases the amount available for consumption the most:

$$\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) := \max_{q \in \mathbf{R}^{13}} Y^\top q$$

$$\text{subject to}$$

$$X^\top q \leq \hat{\rho} \quad \text{and} \quad q^\top q \leq 1, \tag{4.14}$$

where $\hat{\rho}$ in Chapter 3 is redefined as

$$\begin{aligned} \hat{\rho} &= \rho && \text{when} \quad m = 0. \\ &= \begin{bmatrix} \rho \\ 0 \end{bmatrix} && \text{when} \quad m = 1, \end{aligned}$$

where $\rho^{\top} = \begin{bmatrix} \frac{\dot{z}}{\bar{z}} & 0 & 0 & 0 \end{bmatrix}$.

In particular, for characterising and testing for existence of lpcaps satisfying (4.12), we focus, as in Chapter 3 , on the special case of problem (4.14) when $\dot{z} = 0$, which we rewrite for ready reference in the rest of the paper as[10]

$$\mathcal{V}(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0) := \max_{q \in \mathbf{R}^{13}} Y^{\top} q$$

$$\text{subject to}$$

$$X^{\top} q \leq 0_{4+m} \quad \text{and} \quad q^{\top} q \leq 1, \tag{4.15}$$

The Lagrangian of problem (4.15) can be written as[11]

$$L\Big|_{\dot{z}=0} = \left[Y^{\top} q - \beta^{\top}[X^{\top} q - \hat{\rho}] - \gamma[q^{\top} q - 1]\right]\Bigg|_{\hat{\rho}=0_{4+m}}. \tag{4.16}$$

The Kuhn-Tucker necessary (and sufficient) conditions for this problem are[12]

$$\begin{aligned} Y - X\beta - 2\gamma q = 0_{13} \\ X^{\top} q \leq 0_{4+m}, \quad \beta \geq 0_{4+m}, \qquad \beta_i X_i^{\top} q = 0 \; \forall \, i = 1, \ldots, 4+m \\ q^{\top} q \leq 1, \quad \gamma \geq 0, \quad \gamma[q^{\top} q - 1] = 0. \end{aligned} \tag{4.17}$$

Let the mappings of the solution and the associated Lagrange multipliers at the optimum of problem (4.15) obtained by solving the Kuhn-Tucker conditions (4.17) be given by $q_X : \mathbf{R}^{26} \longmapsto \mathbf{R}^{13}$, $\beta_X : \mathbf{R}^{26} \longmapsto \mathbf{R}^{4+m}$, and $\gamma_X : \mathbf{R}^{26} \longmapsto \mathbf{R}$ with image[13]

$$\langle q^*, \beta^*, \gamma^* \rangle \in \Big\langle q_X(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}), \quad \beta_X(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}), \gamma_X(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}) \Big\rangle\Bigg|_{\dot{z}=0}.$$

Analogous to Chapter 3 , denote the the index set of constraints in $X^{\top} q \leq 0_4$ that bind at the optimum of the problem (4.15) by J and let X^J be the matrix whose columns are the columns of matrix X corresponding to indices in the set J and β^J be the vector of Lagrange multipliers of the constraints in $X^{\top} q \leq 0_4$ that bind at the optimum of

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[10] Note, when $\frac{\dot{z}}{\bar{z}} = 0$, $\hat{\rho} = 0_{4+m}$.

[11] This, along with the solution vector, is analogous to the Lagrangian of problem (3.37) and its solution in Chapter 3 , with policy reform vector in the levels of policy variables $\dot{\nu}$ being replaced by lpcap q.

[12] These also follow from Chapter 3 after replacing the policy reform vector in the levels of active policy variables $\dot{\nu}$ by lpcap q.

[13] These mappings are set-valued to allow for multiple solutions to problem (4.15).

the problem (4.15).[14] Let the elements of J arranged in ascending order be $w_1, \ldots, w_J$. Let the elements of set J^c, which is the complement of set J, arranged in ascending order be $o_1, \ldots, o_{J^c}$. J^c is the index set of constraints in $X^\top q \leq 0_4$ that do not bind at the optimum.[15] It follows from the Kuhn-Tucker conditions in (4.17) that the Lagrange multipliers of these constraints take value zero at the optimum.

Remark 9 *The elasticity analogue of Lemma 2 in Chapter 3 follows by replacing the optimal policy reform vector in the levels of policy variables* $\dot{\nu}^*$ *by the optimal lpcap* q^* *and redefining* X *and* Y *using (4.10) and (4.11), resp. This yields the following formulae to compute the solution of problem (4.15).*

$$\begin{aligned}
\beta^J &= \left(X^{J\top} X^J\right)^{-1} X^{J\top} Y, \\
\beta^*_{w_j} &= \beta^J_{w_j} \qquad \forall\, j = 1, \ldots, J, \\
\beta^*_{o_j} &= 0 \qquad\quad \forall\, j = 1, \ldots, J^c, \\
\gamma^* &= \frac{\sqrt{(Y - X^J\beta^J)^\top (Y - X^J\beta^J)}}{2}, \\
q^* &= \frac{Y - X^J\beta^J}{2\gamma^*} \qquad\qquad \textit{if} \quad \gamma^* \neq 0, \\
q^* &= 0 \in q_X(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0) \qquad \textit{if} \quad \gamma^* = 0.
\end{aligned} \tag{4.18}$$

It is important to note that the elasticities that define matrix X and vector Y can be evaluated at the status-quo using formulae in (4.2) and the data prevailing at the status-quo. Thus, X and Y are fixed at the status-quo. This means, that the solution to problem (4.15) can be readily computed using the formulae given in (4.18) in conjunction with status-quo data.

Remark 10 *Analogous to Lemma 3 in Chapter 3 , the empirical test for the existence of lpcaps satisfying (4.12) at the status-quo requires checking if* $\gamma^* = 0$, *where* γ^* *is computed using (4.18) and the status-quo data.*

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[14] See Chapter 3 for more details on how the matrix X^J and vector β^J are constructed.

[15] As in Chapter 3 , with an abuse of notation, we assume J and J^c denote also the cardinalities of sets J and J^c, resp.

4.3 Functional Forms for Energy-using or Energy-generating Production Technologies

Our model includes energy-generating technologies in the coal-fired electricity and renewable energy sectors as well as the energy using technology of the aggregated sector $\mathcal{Y}$. To estimate these technologies econometrically, we need to first specify suitable forms for production functions F, E^C, and E^R that represent technologies generating output $\mathcal{Y}$, coal-fired electricity, and renewable energy, resp. The properties of a technology set put restrictions on the form of the production function that can be used to represent it.

In this section, we present some axioms that we feel are relevant for the intended-output producing technologies included in our model. We study the implications of these axioms for the production functions that can represent such technologies. We show that the standard Cobb Douglas and CES class of technologies violate some of these proposed axioms. We then present two new functional forms that satisfy our axioms.

4.3.1 Some Relevant Axioms for Intended-output Producing Technologies and Their Implications

Let us define a generic technology set with n inputs and one intended output as

$$\mathbb{T} = \{\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbf{R}^n \times \mathbf{R}_+ \mid \mathbb{x} \text{ can produce } \mathbb{y}\},$$

where $\mathbb{x} \in \mathbf{R}^n_+$ denotes an input vector and $\mathbb{y} \in \mathbf{R}_+$ denotes the amount of intended output produced.

Standard assumptions of classical production theory such as input and output free disposability, possibility of shutting down, and no free lunch continue to remain relevant for the intended-output producing technologies included in our model.

Some Special Features of Intended-output Producing Technologies Employing Inputs of Energy and Fossil Fuel

The usage of inputs such as energy by the technology of sector $\mathcal{Y}$ and coal by the technology of coal-fired electricity generation suggest that the restrictions imposed by such technologies on the way inputs can be combined transcend the conditions that are standardly imposed on intended-output producing technologies. We highlight three additional restrictions:

(1) The use of energy is essential in sector $\mathcal{Y}$ as is also the use of coal in coal-fired electricity generation. In the absence of the energy input, no output can be produced in sector $\mathcal{Y}$, immaterial of the extent of usage of the other inputs. Similarly, no electricity can be produced in coal-fired plants if coal was not used.[16] We, hence, define an essential input following Shephard (1970):

Definition. Input i is an *essential input* of technology $\mathbb{T}$ if

$$\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T}, \qquad \mathbb{x} \neq 0_n, \quad \text{and} \quad \mathbb{x}_i = 0 \quad \Longrightarrow \quad \mathbb{y} = 0.$$

(2) Our intuition suggest that the intended-output producing technologies included in our model impose limits on the extent to which an output can be produced when some inputs are held fixed. For example, it is not possible that arbitrarily increasing usage of coal, while holding labour and capital amounts fixed can indefinitely increase the production of electricity in a coal-fired plant. The extent of capital and labour inputs that went into creation of a coal-fired power plant define its capacity – (defined as the maximum electrical output a power generator can produce without exceeding design thermal limits).[17] We can also argue that usage of coal limits the amount of electricity that can be produced, *i.e.,* arbitrarily increasing labour and capital inputs (or the plant size) can not increase the electrical output production indefinitely when coal is held fixed. In sector $\mathcal{Y}$ too, we can

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[16] Indeed, if energy and coal were not essential for producing outputs of sector $\mathcal{Y}$ and coal-fired plants, then there would have been no major anthropogenic climate change problem.

[17] See, for example, the definition of capacity of a power plant given by U.S. EIA (2015).

argue that labour and capital inputs alone cannot increase output indefinitely when energy input is held fixed, and vice-versa. Shephard (1970) formulates this property rigorously and calls it limitationality of inputs. A combination of n' inputs with indices $s_1, \dots, s_{n'}$ is limitational for a technology if the output cannot be increased indefinitely by increasing the usage of the remaining inputs whenever the usage of inputs $s_1, \dots, s_{n'}$ is restricted to be below some given fixed amounts:[18]

Definition. A combination of n' inputs with indices $\langle s_1, \dots, s_{n'} \rangle$ and $0 < n' \leq n$ is *limitational* for technology $\mathbb{T}$ if, for all $\langle \bar{\mathbb{x}}_{s_1}, \dots, \bar{\mathbb{x}}_{s_{n'}} \rangle \in \mathbf{R}_+^{n'}$, the set

$$\left\{ \mathbb{y}' \geq 0 \,\middle|\, \langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T} \text{ with } \mathbb{x}_{s_j} \leq \bar{\mathbb{x}}_{s_j} \ \forall j = 1, \dots, n' \right\}$$

is bounded.

Remark 11 *If a combination of n' inputs with indices $\langle s_1, \dots, s_{n'} \rangle$ is limitational for technology $\mathbb{T}$, then inputs $s_1, \dots, s_{n'}$ are also essential for technology $\mathbb{T}$. (See Shephard (1970))*

(3) The third additional feature of the non-emission generating technologies that are relevant for our model is the high degree of complementarity between the usage of energy inputs and the other inputs in sector $\mathcal{Y}$ and between the usage of coal and use of other inputs in coal-fired plants. For example, the thermodynamic laws imply that coal is not substitutable for other inputs such as labour and capital in coal-fired electricity generation. Energy used in production of output in sector $\mathcal{Y}$ cannot be easily substituted by other inputs such as capital and labour. In fact, energy is required to operate capital inputs such as machines and tools.

The degree of complementarity (or substitutability) between inputs is often studied in the literature by employing the concept of the Hicks-Allen elasticity of substitution. Suppose

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[18] For example, if $n = 5$ and $n' = 3$, then three out of the five inputs are limitational. If these inputs are the first, second and fourth inputs then, the input indices corresponding to these are $s_1 = 1$, $s_2 = 2$, and $s_3 = 4$.

a twice continuously differentiable function $f : \mathbf{R}_{+}^{n} \longrightarrow \mathbf{R}_{+}$ with image

$$\mathbb{y} = f(\mathbb{x})$$

represents technology $\mathbb{T}$, *i.e.,*

$$\mathbb{T} \equiv \{\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbf{R}_{+}^{n+1} \mid \mathbb{y} \leq f(\mathbb{x})\}. \tag{4.19}$$

The marginal rate of technical substitution between any two inputs i and i', evaluated at $\mathbb{x} \in \mathbf{R}_{+}^{n}$, is given by

$$MRTS_{i,i'}(\mathbb{x}) := \frac{f_i(\mathbb{x})}{f_{i'}(\mathbb{x})}.$$

The Hicks-Allen elasticity of substitution between any two inputs i and i' is evaluated along an isoquant. Evaluated at any point $\mathbb{x} \in \mathbf{R}_{+}^{n}$, it is the percentage change in their ratio $\frac{\mathbb{x}_{i'}}{\mathbb{x}_i}$ per unit percentage change in the marginal rates of technical substitution $MRTS_{i,i'}(\mathbb{x})$ between the two inputs, along the isoquant passing through $\mathbb{x}$. It is denoted by $\sigma_{i,i'}(\mathbb{x})$, where[19]

$$\Big(\sigma_{i,i'}(\mathbb{x})\Big)^{-1} = \frac{\big[2 f_i f_{i'} f_{ii'} - f_i^2 f_{i'i'} - f_{i'}^2 f_{ii}\big]\, \mathbb{x}_i \mathbb{x}_{i'}}{\big[\mathbb{x}_i f_{i'} + \mathbb{x}_{i'} f_i\big]\, f_i f_{i'}}.$$

Definition. Suppose f represents technology $\mathbb{T}$. Then two inputs i and i' of technology $\mathbb{T}$ are *highly substitutable at* $\mathbb{x} \in \mathbf{R}_{+}^{n}$ if $\sigma_{i,i'}(\mathbb{x}) > 1$ and are *highly complementary at* $\mathbb{x} \in \mathbf{R}_{+}^{n}$ if $\sigma_{i,i'}(\mathbb{x}) < 1$. If $\sigma_{i,i'}(\mathbb{x}) > 1$ (resp., $\sigma_{i,i'}(\mathbb{x}) < 1$) at *all* $\mathbb{x} \in \mathbf{R}_{+}^{n}$ then inputs i and i' of technology $\mathbb{T}$ are *highly substitutable* (resp. *highly complementary*).

Assumptions on Intended-output Producing Technologies and Their Consequences for Functional Representation of Technologies

The set of axioms that we feel are relevant for the intended-output producing technologies, which form a part of our model, include both the standard classical axioms and additional axioms capturing essentiality, limitationality, and high degree of complementarity of inputs.

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[19] See, for instance, Allen (1938), p. 340-3, and p. 503-9. All the first-order and second-order partial derivatives of f are evaluated at $\mathbb{x}$.

Assumptions.

A1 $\mathbb{T}$ is closed.

A2 For every $\mathbb{x} \in \mathbf{R}^n_+$ the set $\mathbb{P}(\mathbb{x}) := \{\mathbb{y} \geq 0 \mid \langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T}\}$ is bounded.

A3 $\mathbb{T}$ satisfies free output disposability: $\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T}$ and $\mathbb{y}' \leq \mathbb{y}$ implies $\langle \mathbb{x}, \mathbb{y}' \rangle \in \mathbb{T}$.

A4 $\mathbb{T}$ satisfies free input disposability: $\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T}$ and $\mathbb{x}' \geq \mathbb{x}$ implies $\langle \mathbb{x}', \mathbb{y} \rangle \in \mathbb{T}$.

A5 $\mathbb{T}$ satisfies shutdown and no free lunch: $0_{n+1} \in \mathbb{T}$ and if $\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T}$ with $\mathbb{x} = 0_n$ then $\mathbb{y} = 0$.

A6 Any combination of $n - 1$ inputs is limitational for technology $\mathbb{T}$.

A7 All inputs are essential for technology $\mathbb{T}$.

A8 $\mathbb{T}$ is convex.

A9 $\mathbb{T}$ satisfies constant returns to scale: $\langle \mathbb{x}, \mathbb{y} \rangle \in \mathbb{T} \implies \langle \lambda \mathbb{x}, \lambda \mathbb{y} \rangle \in \mathbb{T}$ for all $\lambda \geq 0$.

A10 Suppose input i is energy or coal. Then, for all inputs i, i' of technology $\mathbb{T}$ such that $i' \neq i$, i and i' are highly complementary.

Implications of Assumptions A1 to A10.

Assumptions **A1** to **A3** imply that there exists a continuous production function $f : \mathbf{R}^n_+ \longrightarrow \mathbf{R}_+$ with image

$$f(\mathbb{x}) := \max\{\mathbb{y} \in \mathbb{P}(\mathbb{x})\}$$

that represents technology $\mathbb{T}$, *i.e.,* f satisfies (4.19).

In addition, the following are true:

(i) Suppose f is also differentiable in the interior of its domain, $\mathbf{R}^n_{++}$. Then Assumption **A4** implies $f_i := \frac{\partial f}{\partial x_i} \geq 0$ for all $i = 1, \ldots, n$.

(ii) Assumption **A5** implies $f\left(0_n\right) = 0$.

(iii) Assumption **A6** implies that, for any combination of $n-1$ input indices $\langle s_1, \ldots, s_{n-1} \rangle$, if $\langle \bar{x}_{s_1}, \ldots, \bar{x}_{s_{n-1}} \rangle \in \mathbf{R}^{n-1}_+$ then

$$y\left(\bar{x}_{s_1}, \ldots, \bar{x}_{s_{n-1}}\right) := \sup_{x \in \mathbf{R}^n_+} \left\{ f\left(x\right) \;\middle|\; \langle x_{s_1}, \ldots, x_{s_{n-1}} \rangle \leq \langle \bar{x}_{s_1}, \ldots, \bar{x}_{s_{n-1}} \rangle \right\} < \infty.$$

(iv) Assumption **A7** implies that for any $i = 1, \ldots, n$, if $x \in \mathbf{R}^n_+$ with $x_i = 0$ and $x \neq 0_n$ then $f\left(x\right) = 0$.

(v) Assumption **A8** implies that f is a concave function.

(vi) Assumption **A9** implies $f\left(\lambda x\right) = \lambda f\left(x\right)$ for all $\lambda \in \mathbf{R}_+$.

(vii) Suppose f is twice continuously differentiable. Then Assumption **A10** implies $\sigma_{i,i'}(x) < 1$ for all $x \in \mathbf{R}^n_+$ and all $i' = 1, \ldots, n$ and $i' \neq i$.

4.3.2 Some Functional Forms for Representing Energy-using or Energy-generating Technologies

Production functions are used in our model to represent functionally technologies of coal-fired electricity generation, renewable energy generation, and the aggregated sector $\mathcal{Y}$. Coal-fired power generation and sector $\mathcal{Y}$ use three inputs each: coal-fired power plants employ capital, labour, and coal, while sector $\mathcal{Y}$ employs capital, labour, and energy. The renewable energy sector is assumed to employ two inputs – labour and capital – to tap fixed (abundant) amounts of renewable resources. Thus, in our model, the number of inputs is $n = 2$ or $n = 3$, depending on the intended-output producing technology considered.

Three classes of functional forms that are employed in this paper are discussed below. The technologies representing all these functional forms satisfy Assumptions A1 to A3. We discuss the additional properties of these three classes below.

The Cobb-Douglas (CD) Case

$$\mathbb{y} = \mathscr{f}\left(\mathbb{x}\right) = A \prod_{i=1}^{n} \mathbb{x}_i^{\theta_i}, \quad A > 0;\ \theta_i \geq 0\ \forall\, i = 1, \ldots, n;\ \sum_{i=1}^{n} \theta_i \leq 1.$$

The properties of this functional form are well-known. The technology represented by this functional form satisfies Assumptions A4, A5, A7, A8 if $\sum_i \theta_i \leq 1$, and A9 if $\sum_i \theta_i = 1$.

It violates Assumptions A6 and A10. None of the inputs is limitational for this technology – output can be increased indefinitely by using more of other inputs when an input is held fixed. The elasticity of substitution between any two inputs is constant and equal to one. Thus, energy (resp., coal) is neither highly complementary to other inputs nor is highly substitutable for other inputs in sector $\mathcal{Y}$ (resp., in coal-fired plants).

The Non-nested and Nested CES Production Functions

This class of production functions has also been greatly studied and employed in the literature. Empirical works distinguish between non-nested and nested CES production functions:[20]

$$\mathbb{y} = \mathscr{f}\left(\mathbb{x}\right) = A\left(\sum_{i=1}^{n} \theta_i \mathbb{x}_i^{\rho}\right)^{\frac{1}{\rho}} \qquad \text{(The non-nested case)}$$

$$A > 0;\ \theta_i \geq 0\ \forall\, i = 1, \ldots, n;\ \rho \leq 1;\ \rho \neq 0.$$

To define the class of nested CES production functions, let $\mathcal{J}$ be a partition of the set of input indices $I = \{1, \ldots, n\}$ with cardinality $|\mathcal{J}|$. Let the elements of $\mathcal{J}$ be denoted by $J_1, \ldots, J_{|\mathcal{J}|}$. Then the nested CES production function corresponding to the nested

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[20] It is well known that the limiting case when $\rho \longrightarrow 0$ corresponds to the Cobb Douglas technology.

structure associated with partition $\mathcal{J}$ of inputs is given by[21]

$$\mathbb{y} = f\left(\mathbb{x}\right) = A\left(\sum_{j=1}^{|\mathcal{J}|}\left(\sum_{i \in J_j} \theta_{ij}\mathbb{x}_i^{\rho_j}\right)^{\frac{\rho}{\rho_j}}\right)^{\frac{1}{\rho}} \qquad \text{(The nested case)}$$

$A > 0;\ \theta_{ij} \geq 0\,\forall\, i = 1, \ldots, n,\ j = 1, \ldots, |\mathcal{J}|;\ \rho_j \leq 1,\ \rho_j \neq 0\,\forall\, j = 1, \ldots, |\mathcal{J}|;\ \rho \leq 1,\ \rho \neq 0.$

It is well documented that when $\rho > 0$, the technologies represented by this class of functions satisfy Assumptions A4, A5, A8, and A9. However they do not satisfy Assumptions A6 and A7 – none of the inputs are essential and, hence, Remark 4 implies that no $n-1$ combination of inputs is limitational.

On the other hand, when $\rho < 0$, the technologies satisfy Assumptions A4, A8, and A9. Assumptions A5 and A7 hold in the limit: $\lim_{\mathbb{x} \longrightarrow 0_n} f\left(\mathbb{x}\right) = 0$ and $\lim_{\mathbb{x}_i \longrightarrow 0} f\left(\mathbb{x}\right) = 0$ for all $i = 1, \ldots, n$. But these technologies too do not satisfy Assumption A6, *i.e.,* no $n-1$ combination of inputs is limitational (see Shephard (1970)).

In the non-nested case, the elasticity of substitution between any two inputs $i, i' = 1, \ldots, n$ is constant and is given by $\sigma_{i,i'}\left(\mathbb{x}\right) = \frac{1}{1-\rho}$. Hence, the inputs are highly complementary if $\rho < 0$ and highly substitutable if $\rho \in (0, 1)$.

Limitational Variable Elasticity of Substitution (LVES) Production Function

The Cobb Douglas and CES production functions do not satisfy limitationality of inputs. They are also associated with constant elasticity of substitution between any two inputs.[22] In this paper, we introduce two new functional forms for the production functions that fall into (what we call) the class of "limitational variable elasticity of substitution" (LVES) production functions.

As the name suggests, this class includes production functions which represent technolo-

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[21] For example, if $n = 3$ and $\mathcal{J} = \{J_1, J_2\}$, where $J_1 = \{1, 2\}$ and $J_2 = \{3\}$, then

$$\mathbb{y} = f\left(\mathbb{x}_1, \mathbb{x}_2, \mathbb{x}_3\right) = A\left[\left(\theta_{11}\mathbb{x}_1^{\rho_1} + \theta_{21}\mathbb{x}_2^{\rho_1}\right)^{\frac{\rho}{\rho_1}} + \left(\theta_{32}\mathbb{x}_3^{\rho_2}\right)^{\frac{\rho}{\rho_2}}\right]^{\frac{1}{\rho}}.$$

[22] More accurately, in the class of CES functions, this is true for the non-nested case. For the nested case, this is true of any two inputs in the same nest.

gies for which inputs are limitational and the Hicks-Allen elasticity of substitution between inputs varies along isoquants in the input space. The two new functional forms we introduce are

$$\mathbb{y} = f\left(\mathbb{x}\right) = A\left(\frac{\prod_{i=1}^{n}\mathbb{x}_i^{\theta_i}}{\mu + \sum_{i=1}^{n}\mathbb{x}_i^{\theta_i}}\right) \qquad \text{(LVES-1)}$$
$$A > 0;\ 0 \leq \theta_i \leq 1\,\forall\, i = 1, \ldots, n;\ \mu > 0.$$

$$\mathbb{y} = f\left(\mathbb{x}\right) = A\left(\frac{\prod_{i=2}^{n}\mathbb{x}_i^{\theta_i}}{\mu + \sum_{i=2}^{n}\left(\frac{\mathbb{x}_i}{\mathbb{x}_1}\right)^{\theta_i}}\right) \qquad \text{(LVES-2)}$$
$$A > 0;\ 0 \leq \theta_i \leq 1\,\forall\, i = 2, \ldots, n;\ \mu > 0.$$

The technologies represented by both LVES-1 and LVES-2 satisfy Assumptions A4 to A7 and A10. Thus, any selection of $n-1$ inputs are limitational and, hence, Remark 4 implies that all inputs are essential. In addition, we conjecture that both technologies satisfy Assumption A8, *i.e.,* we conjecture that both functions are concave. It is clear that while LVES-1 technology does not exhibit constant returns to scale (*i.e.,* does not satisfy Assumptions A9)), LVES-2 technology does.

Properties of LVES-1 production function.

(i) Function f is increasing in inputs

$$f_i(\mathbb{x}) \equiv \frac{\partial \mathbb{y}}{\partial \mathbb{x}_i} = \frac{A\theta_i \mathbb{x}_i^{\theta_i - 1}\prod_{i' \neq i}\mathbb{x}_{i'}^{\theta_{i'}}\left(\mu + \sum_{i' \neq i}\mathbb{x}_{i'}^{\theta_{i'}}\right)}{\left(\mu + \sum_{i=1}^{n}\mathbb{x}_i^{\theta_i}\right)^2} > 0, \qquad \forall\, i = 1, \ldots, n.$$

(ii) Function f exhibits diminishing marginal productivity with respect to all inputs:

$$f_{ii}(\mathbb{x}) \equiv \frac{\partial^2 \mathbb{y}}{\partial \mathbb{x}_i^2} = \frac{-A\theta_i \mathbb{x}_i^{\theta_i - 2}\prod_{i' \neq i}\mathbb{x}_{i'}^{\theta_{i'}}\left(\mu + \sum_{i' \neq i}^{n}\mathbb{x}_{i'}^{\theta_{i'}}\right)\left((1+\theta_i)\mathbb{x}_i^{\theta_i} + (1-\theta_i)\left(\sum_{i' \neq i}^{n}\mathbb{x}_{i'}^{\theta_{i'}} + \mu\right)\right)}{\left(\mu + \sum_{i=1}^{n}\mathbb{x}_i^{\theta_i}\right)^3} < 0,$$
$$i = 1, \ldots, n.$$

(iii) Function f exhibits variable elasticity of substitution with elasticity of substitution between any two inputs being less than one, *i.e.,* inputs are highly complementary:

$$\sigma_{i,j}(\mathbb{x}) = \frac{\theta_i\left(\mu + \sum_{i' \neq i} \mathbb{x}_{i'}^{\theta_{i'}}\right) + \theta_j\left(\mu + \sum_{i' \neq j} \mathbb{x}_{i'}^{\theta_{i'}}\right)}{\theta_i\left(\mu + \sum_{i' \neq i} \mathbb{x}_{i'}^{\theta_{i'}}\right) + \theta_j\left(\mu + \sum_{i' \neq j} \mathbb{x}_{i'}^{\theta_{i'}}\right) + \theta_i\theta_j\left(\mathbb{x}_i^{\theta_i} + \mathbb{x}_j^{\theta_j}\right)} < 1, \quad \forall\, i, j = 1, \ldots, n.$$

(iv) It is clear that all inputs are essential under function f.

(v) We show that any $n-1$ combination of inputs is limitational for technology $\mathbb{T}$ represented by a LVES-1 production function f. To ease notation, without loss of generality, we prove that the combination of first $n-1$ inputs is limitational.[23] Holding the first $n-1$ inputs fixed at levels $\langle \bar{\mathbb{x}}_1, \ldots, \bar{\mathbb{x}}_{n-1} \rangle$, we check the limit of the output that can be produced by arbitrarily increasing the remaining input $\mathbb{x}_n$. To do so, let's define the product $\prod_{i=1}^{n-1} \bar{\mathbb{x}}_i^{\theta_i} = \bar{P}_{n-1}$. Then,

$$\begin{aligned}
\lim_{\mathbb{x}_n \longrightarrow \infty} f\left(\bar{\mathbb{x}}_1, \ldots, \bar{\mathbb{x}}_{n-1}, \mathbb{x}_n\right) &= \lim_{\mathbb{x}_n \longrightarrow \infty} A\left(\frac{\bar{P}_{n-1}\mathbb{x}_n^{\theta_n}}{\mu + \sum_{i=1}^{n-1} \bar{\mathbb{x}}_i^{\theta_i} + \mathbb{x}_n^{\theta_n}}\right) \\
&= \lim_{\mathbb{x}_n \longrightarrow \infty} A\left(\frac{\bar{P}_{n-1}}{\frac{\mu}{\mathbb{x}_n^{\theta_n}} + \sum_{i=1}^{n-1} \frac{\bar{\mathbb{x}}_i^{\theta_i}}{\mathbb{x}_n^{\theta_n}} + 1}\right) \\
&= A\bar{P}_{n-1} < \infty
\end{aligned}$$

Hence, the $n-1$ inputs are limitational.

Properties of LVES-2 production function

$$\mathbb{y} = f(\mathbb{x}) = A\left(\frac{\prod_{i=2}^{n} \mathbb{x}_i^{\theta_i}}{\mu + \sum_{i=2}^{n}\left(\frac{\mathbb{x}_i}{\mathbb{x}_1}\right)^{\theta_i}}\right) \qquad \text{(LVES-2)}$$

$$A > 0;\ 0 \leq \theta_i \leq 1\ \forall\, i = 2, \ldots, n;\ \mu > 0.$$

(i) Function f is increasing in inputs

$$f_i(\mathbb{x}) \equiv \frac{\partial \mathbb{y}}{\partial \mathbb{x}_i} = \frac{A\theta_i \mathbb{x}_i^{\theta_i - 1} \prod_{i' \neq i} \mathbb{x}_{i'}^{\theta_{i'}} \left(\mu + \sum_{i' \neq i}\left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1}\right)^{\theta_{i'}}\right)}{\left(\mu + \sum_{i=2}^{n}\left(\frac{\mathbb{x}_i}{\mathbb{x}_1}\right)^{\theta_i}\right)^2} > 0, \qquad \forall\, i = 2, \ldots, n.$$

---

[23] The remaining $n-1$ possible combinations can be shown to be limitational in an exactly similar manner.

$$\mathscr{f}_1(\mathbb{x}) \equiv \frac{\partial \mathbb{y}}{\partial \mathbb{x}_1} = \frac{A \prod_i^n \mathbb{x}_i^{\theta_i} \left(\sum_{i=2}^n \theta_i \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} \right)}{\mathbb{x}_1 \left(\mu + \sum_{i=2}^n \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} \right)^2} > 0.$$

(ii) Function $\mathscr{f}$ exhibits diminishing marginal productivity with respect to all inputs:

$$\mathscr{f}_{ii}(\mathbb{x}) \equiv \frac{\partial^2 \mathbb{y}}{\partial \mathbb{x}_i^2} = \frac{-A\theta_i \mathbb{x}_i^{\theta_i - 2} \prod_{i' \neq i} \mathbb{x}_{i'}^{\theta_{i'}} \left(\mu + \sum_{i' \neq i}^n \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} \right) \left((1+\theta_i) \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + (1-\theta_i) \left(\sum_{i' \neq i}^n \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} + \mu \right) \right)}{\left(\mu + \sum_{i=2}^n \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} \right)^3} < 0,$$

$$\forall\, i = 2, \ldots, n.$$

When $n = 3$, we have[24]

$$\mathscr{f}_{11}(\mathbb{x}) \equiv \frac{\partial^2 \mathbb{y}}{\partial \mathbb{x}_1^2} = \frac{-A \mathbb{x}_i^{\theta_i} \mathbb{x}_j^{\theta_j} \left(\begin{array}{c} \sum\limits_{i'=i,j} \mu(\theta_{i'} + \theta_{i'}^2) \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} + \sum\limits_{i'=i,j} (\theta_{i'} - \theta_{i'}^2) \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{2\theta_{i'}} \\ + \left((\theta_i - \theta_j)^2 + \theta_i + \theta_j \right) \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \end{array} \right)}{\mathbb{x}_2^2 \left(\mu + \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right)^3} < 0,$$

$$\forall\, i, j \neq 1.$$

(iii) Function $\mathscr{f}$ is concave as its Hessian is negative semi-definite.[25]

(iv) Function $\mathscr{f}$ exhibits variable elasticity of substitution with elasticity of substitution between any two inputs being less than one, *i.e.,* inputs are highly complementary:

$$\sigma_{i,j}(\mathbb{x}) = \frac{\theta_i \left(\mu + \sum_{i' \neq i} \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} \right) + \theta_j \left(\mu + \sum_{i' \neq j} \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} \right)}{\theta_i \left(\mu + \sum_{i' \neq i} \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} \right) + \theta_j \left(\mu + \sum_{i' \neq j} \left(\frac{\mathbb{x}_{i'}}{\mathbb{x}_1} \right)^{\theta_{i'}} \right) + \theta_i \theta_j \left(\left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \left(\frac{\mathbb{x}_j}{x_1} \right)^{\theta_j} \right)} < 1,$$

$$\forall\, i = 2, \ldots, n.$$

When $n = 3$

$$\sigma_{1,i}(\mathbb{x}) = \frac{\left(\theta_i \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \theta_j \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) \left(\theta_i \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \theta_j \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} + \theta_i \left(\mu + \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) \right)}{\left(\begin{array}{c} \left(\theta_i \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \theta_j \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) \left(\theta_i \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \theta_j \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} + \theta_i \left(\mu + \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) \right) \\ + \theta_i^3 \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} \left(\left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) + \mu \theta_i \left(\theta_i^2 \left(\frac{\mathbb{x}_i}{\mathbb{x}_1} \right)^{\theta_i} + \theta_j^2 \left(\frac{\mathbb{x}_j}{\mathbb{x}_1} \right)^{\theta_j} \right) \end{array} \right)} < 1,$$

$$\forall\, i, j \neq 1.$$

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[24] For the case $n = 2$, assume $\theta_3 = 0$ in the formulations below.

[25] See proof in the Appendix.

(v) It is clear that all inputs are essential under function f.

(vi) Any combination of $n-1$ inputs is limitational for $\mathbb{T}$ represented by function f.

We first show that input 1 combined with $n-2$ of the remaining inputs is limitational. WOLOG, we select the first $n-1$ inputs (input 1 is included in this set).[26]

Suppose $\prod_{i=2}^{n-1} \bar{\mathbb{x}}_i^{\theta_i} = \bar{P}_{n-1}$. Then,

$$\begin{aligned}
\lim_{\mathbb{x}_n \longrightarrow \infty} f\left(\bar{\mathbb{x}}_1, \ldots, \bar{\mathbb{x}}_{n-1}, \mathbb{x}_n\right) &= \lim_{\mathbb{x}_n \longrightarrow \infty} A \left(\frac{\bar{P}_{n-1} \mathbb{x}_n^{\theta_n}}{\mu + \sum_{i=2}^{n-1} \left(\frac{\bar{\mathbb{x}}_i}{\bar{\mathbb{x}}_1}\right)^{\theta_i} + \left(\frac{\mathbb{x}_n}{\bar{\mathbb{x}}_1}\right)^{\theta_n}} \right) \\
&= \lim_{\mathbb{x}_n \longrightarrow \infty} A \left(\frac{\bar{P}_{n-1}}{\frac{\mu}{\mathbb{x}_n^{\theta_n}} + \sum_{i=2}^{n-1} \left(\frac{\bar{\mathbb{x}}_i}{\bar{\mathbb{x}}_1}\right)^{\theta_i} \left(\frac{1}{\mathbb{x}_n}\right)^{\theta_n} + \left(\frac{1}{\bar{\mathbb{x}}_1}\right)^{\theta_n}} \right) \\
&= A \bar{P}_{n-1} \bar{\mathbb{x}}_1^{\theta_n} < \infty
\end{aligned}$$

We now show that inputs 2 to n are limitational. Suppose $\prod_{i=2}^{n} \bar{\mathbb{x}}_i^{\theta_i} = \bar{P}_n$. Then,

$$\begin{aligned}
\lim_{\mathbb{x}_n \longrightarrow \infty} f\left(\mathbb{x}_1, \bar{\mathbb{x}}_2, \ldots, \bar{\mathbb{x}}_n\right) &= \lim_{\mathbb{x}_1 \longrightarrow \infty} A \left(\frac{\prod_{i=2}^{n} \mathbb{x}_i^{\theta_i}}{\mu + \sum_{i=2}^{n} \left(\frac{\mathbb{x}_i}{\mathbb{x}_1}\right)^{\theta_i}} \right) \\
&= A \frac{\bar{P}_n}{\mu} < \infty
\end{aligned}$$

(vii) f is linear homogeneous (*i.e.*, $\mathbb{T}$ exhibits crs) if $\sum_{i=2}^{n} \theta_i = 1$.

Table 4.1 below summarises the properties of all the functions discussed above.

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[26] The remaining cases of combining input 1 with $n-2$ of the remaining inputs can be shown to be limitational in an exactly similar manner.

Table 4.1: Table of properties satisfied by CD, CES, and LVES production functions

	FOD	**FID**	**SD and NFL**	**LIML**	**ESSEN**	**CONV**	**CRS**	**VES**	**HIGH COMPL**
CD (crs)	✓	✓	✓	✗	✓	✓	✓	✗	✗
CES (non-nested, $\rho > 0$)	✓	✓	✓	✗	✗	✓	✓	✗	✗
CES (non-nested, $\rho < 0$)	✓	✓	in the limit	✗	in the limit	✓	✓	✗	✓
LVES-1	✓	✓	✓	✓	✓	✓*	✗	✓	✓
LVES-2	✓	✓	✓	✓	✓**	✓	✓***	✓	✓

FOD: free output disposability
FID: free input disposability
SD and NFL: shut down and no free lunch
LIML: limitationality
ESSEN: essentiality
CONV: convexity
CRS: constant returns to scale
VES: variable elasticity of substitution
HIGH COMPL: high complementarity
✓*: true for our estimated technologies
✓**: input 1 is essential in the limit. All other inputs are essential
✓***: possible if $\sum_{i=2}^{n} \theta_i = 1$

4.4 Data and Implementation

4.4.1 Data Description

Data was collected for 30 provinces in China for the years 2006 to 2012. Data on several variables in our model is not directly available. For these variables, we obtain estimates from other works or from data on related variables.

Regional Output Data

Annual data on the gross regional product (GRP) of each province in 2000 prices was collected from China Statistic Yearbooks (2007 to 2013) and was converted into hundreds of million USD.

Data on Capital

In this paper, we adopt the Perpetual Inventory Method (PIM) to estimate the annual total capital stock, which is measured in hundreds of million USD in 2000 prices.[27]

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[27] The PIM computes capital stock $k_{i,t}$ in the i^{th} province and for the t^{th} year as

$$k_{i,t} = k_{i,t-1} \left(1 - \delta_i\right) + I_{i,t},$$

Total capital, so estimated, is decomposed into three parts: k_{TC} is the capital employed by the coal-fired plants in the thermal electricity generating sector, k_R is the capital employed in the renewable energy sector, and k_Y is the capital employed in all other sectors (which include the non-energy producing sector and non-electrical energy producing and gas-fired electricity generation components of the energy sector).

Data on k_{TC} and k_R is not directly available. So we estimate these variables as follows: First, for each province, we compute the ratio of value of fixed assets in the electricity and heat generation sector to the total value of fixed assets. (Data on the value of fixed assets is obtained from China Industry Economy Statistical Yearbook 2007 to 2013.) Then, we compute the capital stock employed in the electricity generating sector for each province by multiplying this ratio with its total capital stock.[28]

The amount of capital stock employed by the thermal coal-fired power generation sector is a proportion of this estimate of capital stock employed in the electricity-generating sector, the proportion being determined by the share of installed capacity of coal-fired power plants in the total capacity of the electricity generating sector. Similarly, we also obtain the amount of capital stock employed in the renewable energy producing sector.[29] The power generation capacity is obtained from the China Electricity Yearbook 2007 to 2013. k_Y is derived residually as the difference between the total capital stock and the estimate of capital employed in the coal-fired and renewable electricity generating sectors.

Data on Labour

Data on total labour employed in each province is obtained from China Statistic Yearbook (2007 to 2013) and is measured in thousands of employed persons.

As in the case of the capital input, labour input is also decomposed into l_{TC} (labour

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where δ_i is the depreciation rate of capital in province i and $I_{i,t}$ denotes the capital asset investment of province i in year t. The capital stock in year 2000 is taken as the initial capital stock. Depreciation rates are derived Zhang et al. (2004).

[28] Thus, we are assuming that the proportion of total capital stock employed in the electricity generating sector is determined by the share of value of fixed assets of this sector in the total value of fixed assets.

[29] We are assuming that a major part of renewable energy is electrical.

employed by the coal-fired electricity generating plants), l_R (labour employed in the renewable energy sector), and l_Y (labour employed in the non-electrical energy producing and gas-fired electricity generation components of the energy sector). Data on allocation of labour input into thermal and renewable energy sectors in each province is available for 2011 from China Electric Power Yearbook (2011). To estimate l_{TC} and l_R for the remaining years we compute the ratios of employment in the thermal coal-fired energy and in the renewable energy sectors in 2011 to the total employment in 2011. These ratios are multiplied with the total employment in all other years to obtain l_{TC} and l_R for the remaining years.[30]

Energy Data

The China Energy Statistics Yearbook (2007 to 2013) provides information on the total amounts of coal, gas, and oil used (denoted by x_C, x_G, and x_O, respectively) in each province, which we measure in 10,000 tons, 100 million m^3, and 10,000 tons units, respectively.

Total energy consumption by a province is the sum of electrical energy produced by it, the non-electrical energy produced by it, and its net import of energy. We assume that only electrical energy can be imported. Hence, we define electrical energy consumption as the sum of electrical energy production plus net imports. Thus, the total energy consumption by a province is

$$\begin{aligned} e &= e_{PROD} + e_{NM} \\ &= \text{electrical energy produced} + \text{non-electrical energy produced} + e_{NM} \\ &= \text{electrical energy consumed} + \text{non-electrical energy produced} \end{aligned}$$

Electrical energy data.

Data on electrical energy consumption by each province is obtained from China Energy

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[30] Thus, due to lack of data, we are assuming that the shares of employment in the thermal coal-fired sector and the renewable sector have remained constant during the years we study.

Statistical Yearbook (2007 to 2013). In addition, for the analysis, we also need data on electricity generated in coal and gas-fired thermal power plants and the renewable sector and on the amounts of coal and gas used in the thermal power plants.

Data on electricity generated by thermal coal-fired plants (denoted by e_{TG}) and renewable power plants (denoted by e_R) is obtained from China Electric Power Yearbook (2007 to 2013) and are converted to million tons of oil equivalent (Mtoe). This source also provides information on the amount of coal used by coal-fired thermal power plants (denoted by x_{TG}), which is measured in ten-thousands of tons.

Province-level data on electricity generated by gas-fired plants (e_{TG}) and on the physical units of gas used in these plants (x_{TG}) is not directly available. Hence, we proceed in the following manner to estimate these for all provinces and for all years.

Gas-fired Power Safety Regulatory Report released by China's National Energy Administration (NEA) provides information on each province's gas-fired power generation capacity, the national gas-fired power generation capacity, and the national gas-fired power generation for the year 2012.[31]

The share of each province's gas-fired power generation capacity in the national gas-fired power generation capacity in 2012 is multiplied by national gas-fired power generation in 2012 to obtain an estimate of the province's gas-fired power generation for 2012. Recall that, in our model, the amount of gas-fired power generation is given by

$$e_{TG} = \frac{\epsilon_G}{h_{TG}} x_{TG}, \tag{4.20}$$

where ϵ_G is the heat factor of gas and h_{TG} is its heat rate. Given the estimate of gas-fired power generation e_{TG} in 2012 and knowledge of ϵ_G and h_{TG}, the physical units of gas employed by gas-fired plants x_{TG} in 2012 can be estimated.[32]

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[31] NEA carried out gas fired power operation safety special regulatory action and inspection work in 2013, and released a Gas-fired Power Safety Regulatory Report in Chinese version.

[32] China Energy Statistical Yearbook gives the China's average energy factor for gas ϵ_G as 38,931 KJ/m^3. The heat rate h_{TG} could be calculated by employing the method suggested in US Energy Information Administration (EIA). The heat rate can be obtained by dividing the energy content content of kWh of electricity (which is 3,412 Btu) by the power plant efficiency. According to Hussy et al. (2014), the average efficiency of gas-fired plant in China is 38.9%. Hence, our calculated value of h_{TG} is 8748.72 Btu/kWh.

To obtain the value of x_{TG} for the remaining years, we assume that the ratio of usage of gas by gas-fired thermal power plants to the total usage of gas is constant throughout this period for any province. Hence, x_{TG} for the remaining years is estimated by multiplying gas usage x_G in each year by this ratio. This, in conjunction with the estimates of h_{TG} and ϵ_G, can be used to estimate the amount of electrical energy produced by gas-fired plants e_{TG} in the remaining years by employing (4.20).

Non-electrical energy

Non-electrical energy is generated from coal, gas, and oil. The estimates of amounts of coal and gas used for generating non-electrical energy (denoted by x_{NC} and x_{NG}, respectively) can be obtained by subtracting the estimates of coal and gas used in thermal power generation (given by x_{TC} and x_{TG}, respectively) from the total annual coal and gas usage (given by x_C and x_G, respectively). Data on output of non-electrical energy from coal, gas, and oil is not directly available. Hence, these are indirectly derived by employing the levels of usage if these inputs, their energy factors, and their heat rates in the non-electrical energy component of the energy sector.

China's average energy factors for coal, gas, and oil were obtained from China Energy Statistical Yearbook as 20,908 KJ/kg, 38,931 KJ/m^3, and 41,816 KJ/kg, respectively. The efficiency factors (which are the inverses of heat rates) provide the efficiency with which heat generated by these fuels is converted into non-electrical energy. The efficiency factors for coal and gas in this sector are obtained from REMIND model as 53% and 73%, respectively.[33] We have assumed that the non-electrical energy is derived from oil with 100% efficiency.

Emission and Forest Data

Province-level data on carbon emissions is not available. Hence, following guidelines of IPCC (2006), we employ data on fossil-fuel usage and emission factors of different fuels

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[33] The REMIND model is given in Luderer et al. (2015).

to compute the gross emissions:

$$\text{gross emission} = x_C\, \epsilon_C\, CC_C + x_G\, \epsilon_G\, CC_G + x_O\, \epsilon_O\, CC_O,$$

where for $i = C, G, O$, ϵ_i is defined as before as the energy- factor for fossil fuel i (the amount of energy liberated per unit combustion of fossil fuel i) and CC_i is its carbon conversion factor of fossil fuel i (the amount of emission generated per unit of energy generated by fossil fuel i). Define $\alpha_i = \epsilon_i\, CC_i$ as the emission factor of fossil fuel i (the amount of emission per unit of fossil-fuel i combusted). Then

$$\text{gross emission} = x_C\, \alpha_C + x_G\, \alpha_G + x_O\, \alpha_O.$$

For $i = C, G, O$, the carbon conversion factor CC_i is obtained from IPCC as default value: 26.0 kg/million KJ (CC_C), 15.3 kg/million KJ (CC_G), and 20.0 kg/million KJ (CC_O). The emission factors can then be computed as 0.5436 kg carbon/kg coal, 5.9564 kg carbon/ 10000 m^3, and 0.8363 kg carbon/kg fuel oil.

The data on afforestation (denoted by a) and current forest area (denoted by f) is obtained from China Statistic Yearbook (2007 to 2013) and is measured in hectares.

Data on total forest expenditure in 2006 is released in China Statistic Yearbook (2007), but we lack the forest expenditure information for the rest years. To obtain the total forest expenditure for the remaining years, we proceed as follows: We assume that the share of total forest expenditure in the total government expenditure remained unchanged in the period of study. Thus, we use the share computed in 2006 and multiply it with the total government expenditure in each year to obtain estimates of the total forest expenditure of the government for all years. The data on total government expenditure was obtained from China Statistic Yearbook (2007 to 2013).

The general forest carbon sequestration rate per unit of area (denoted by s) in China has been estimated as 1.53 Mg/hectare per year in Wang et al. (2014).[34] Thus, net carbon

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[34] The forest carbon sequestration are closely related to forest area, tree species composition, and site conditions. The number used in this chapter is the weighted arithmetic mean for four types of forests in China estimated in Wang et al. (2014) by using the National Forest Resource Inventory data for China collected from 2004 to 2008. *See,* Wang et al. (2014) for more detailed methods.

emission is computed as

$$z_n = \text{gross emission} - s\,a$$

Levelized Costs of Generating Energy and Prices of Fossil Fuels

The levelized cost of generating (LCOG) energy from gas-fired plant in China is obtained from IEA (2010), as 35.81 USD/Mwh and convert to the 4.1647 (100 million USD/Mtoe).

The LCOG non-electrical energy from coal and gas are estimated using the information from REMIND model (Luderer et al., 2015) and formula proposed by US National Renewable Energy Laboratory (NREL).

For $i = C, G$, the LCOG energy from fossil fuel i is calculated using the following formula:

$$\xi_i = \frac{OIC_i CRF_i + FO\&M_i}{8760 CP_i} + VO\&M_i + FC_i$$

where ξ_i is the levelized cost of producing one unit of energy from the fuel i. OIC_i is overnight investment cost, which is measured in USD per-unit installed capacity (USD per kilowatt). CRF_i is capital recovery factor of plant using fossil fuel i. The capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Given a discount rate ρ and n_i facility lifetime of fossil fuel i, the capital recovery factor is given by

$$CRF_i = \frac{\rho(1+\rho)^{n_i}}{[(1+\rho)^{n_i}] - 1}.$$

$FO\&M_i$ and $VO\&M_i$ are the fixed and variable operation and maintenance cost in USD per kWh, respectively. The figure 8760 in the denominator is the number of hours in a year, while CP_i is capacity the factor, a fraction between 0 and 1 representing the portion of a year that the energy plant is generating. FC_i is the fuel cost, which is equal to the market price of fuel i divided by its energy factor ϵ_i. The data on OIC, $O\&M$, and the lifetime n_i for non-electrical coal and gas energy plant used in this study come from the REMIND model (Luderer et al., 2015). Discount rate and capacity factor are from

Rushing et al. (2012) and **?**, respectively.[35]

Then, the LCOG non-electrical energy from coal and gas estimated in our paper are 42.37 and 64.78 USD/Mwh, respectively.[36]

The average market price of coal (denoted by p_C), natural gas (denoted by p_G) and fuel oil (denoted by p_O) in 2012 are 527.75 CNY/ton, 3.19 CNY/m^3, and 9261.92 CNY/ton, which are obtained from the Price Yearbook of China (2013). The USD to CNY exchange rate used in this study is 1 USD = 6.8 CNY.

4.4.2 Implementation

In this section, we provide the empirical procedures used in this paper to implement the elasticity analogue of the theoretical methodology developed in Chapter 3 to firstly, test the existence of efficiency-improving lpcaps (*i.e.,* consumption-increasing, feasible, and emission non-increasing lpcaps) at the status-quo, secondly, to compute the optimal efficiency-improving lpcap and the MAC, and thirdly, to test various hypotheses about possible structures of efficiency-improving lpcaps.

Testing for the Existence of Efficiency-improving lpcaps, the Optimal Efficiency-improving lpcap, and Computing the MAC.

Testing the existence of feasible, consumption-increasing, emission non-increasing lpcaps at a tight status-quo $\bar{S} = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle \in \mathbf{R}^{25}_{+}$ (*i.e.,* testing for the existence of lpcaps satisfying (4.12) with $m = 0$ at $\bar{S}$) requires testing whether the theoretical condition (4.13) in Remark 1 holds with[37]

$$X = \boldsymbol{\chi}.$$

From Remarks (2) and (3) this can be tested by solving problem (4.15) by using the formulae in (4.18) to compute the optimal lpcap q^* and the values of the Lagrange multipliers

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[35] In this paper, we will adopt 3% discount rate and 0.85 capacity factor.

[36] In our paper, we will convert the calculated LCOG to 4.9280 and 7.5343 (100 million USD/Mtoe).

[37] See the case of $m = 0$ in (4.10).

$\langle \beta^*,\ \gamma^* \rangle$ and checking whether $\gamma^* = 0$.

In what follows, we will refer to feasible, consumption-increasing, emission non-increasing lpcaps also as "efficiency-improving reforms".

To compute a measure of MAC that is independent of the units in which active policy variables are measured, first note that, from (4.11) and (4.5), it follows that the value function of the problem (4.15) is

$$\mathcal{V}\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0\right) \;=\; Y \cdot q^* \;=\; \eta^{\mathcal{F}} \cdot q^* =: \frac{\dot{y}^*}{\bar{y}}. \tag{4.21}$$

Applying the envelope theorem to problem (4.15) with $X = \boldsymbol{\chi}$, we have

$$\frac{\partial \mathcal{V}\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0\right)}{\partial \dot{z}} \;=\; \left.\frac{\partial L}{\partial \dot{z}}\right|_{\dot{z}=0} = \frac{\beta_1^*}{\bar{z}} \tag{4.22}$$

where the Lagrangian of problem (4.15) when $m = 0$ is

$$L\Bigg|_{\dot{z}=0} = {\eta^{\mathcal{F}}}^\top q - \beta_1 \left[[{\eta^{\mathcal{Z}}}^\top q - \frac{\dot{z}}{\bar{z}}] - \beta_2\, {\eta^{\mathcal{T}}}^\top q - \beta_3\, {\eta^{\mathcal{L}}}^\top q - \beta_4\, {\eta^{\mathcal{K}}}^\top q - \gamma[q^\top q - 1] \right] \Bigg|_{\dot{z}=0} \tag{4.23}$$

From (4.21) and (4.22), we have

$$\frac{\partial \mathcal{V}\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0\right)}{\partial \frac{\dot{z}}{\bar{z}}} = \frac{\partial \frac{\dot{y}^*}{\bar{y}}}{\partial \frac{\dot{z}}{\bar{z}}} = \beta_1^*$$

This shows that β_1^* measures the proportionate change in consumption per unit proportionate change in the emission cap, and hence it is independent of the units in which active policies are measured. Thus, employing (4.21) and (4.22), we can derive a measure of MAC that is independent of the units in which active policies are measured as

$$\mathcal{MAC}\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, 0\right) := \frac{\partial \dot{y}^*}{\partial \dot{z}} \;= \beta_1^* \frac{\bar{y}}{\bar{z}} \tag{4.24}$$

Intuitively, this definition of MAC measures, starting from the status-quo $\bar{S}$, the change in the level of consumption that is induced by the optimal lpcap q^* per unit change in the emission cap. MAC is measured in units such as dollars per ton of emission.

Testing Hypotheses about the Structures of Efficiency-improving lpcaps Available at the Status-quo

The methodology developed in Chapter 3 can be employed to test several hypotheses regarding the structures of efficiency-improving reforms available at the tight status-quo that take forms such as those given in (4.9).

The following remark presents the elasticity analogues of Theorem 6 and Corollary 7 of Chapter 3 .

Remark 12 *Suppose* $\bar{S} = \langle \Theta, \bar{\nu}, \bar{y}, \bar{z} \rangle$ *is a tight status-quo and* $m = 1$ *so that* $X = \begin{bmatrix} \boldsymbol{\chi} & X_5 \end{bmatrix}$ *in problem (4.15) with* $X_5 = I^\eta$ *or* $X_5 = -I^\eta$*. Let*

$$\langle q^*,\ \beta^*,\ \gamma^* \rangle \ \in \ \left\langle q_X\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right), \quad \beta_X\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right), \ \gamma_X\left(\Theta, \bar{\nu}, \bar{y}, \bar{z}, \dot{z}\right) \right\rangle \Bigg|_{\dot{z}=0} .$$

Suppose $\eta^{\mathcal{F}}$ *and* I^η *are not collinear and there exist feasible, final consumption-increasing, and emission non-increasing lpcaps at* $\bar{S}$*. Then the following are true:*

(i) Any final consumption-increasing, and emission non-increasing lpcap q *implies also* $I^\eta \cdot q > 0$ *if and only if*

$$\left[\gamma^* = 0, \quad \langle \beta_1^*, \ldots, \beta_4^* \rangle \neq 0_4, \quad \beta_5^* > 0\right] \quad \textit{when} \quad X_5 = I^\eta.$$

(ii) Any final consumption-increasing, and emission non-increasing lpcap q *implies also* $I^\eta \cdot q < 0$ *if and only if*

$$\left[\gamma^* = 0, \quad \langle \beta_1^*, \ldots, \beta_4^* \rangle \neq 0_4, \quad \beta_5^* > 0\right] \quad \textit{when} \quad X_5 = -I^\eta.$$

(iii) There exists a final consumption-increasing, feasible, emission non-increasing lpcap q *such that* $I^\eta \cdot q \leq 0$ *and there exists a final consumption-increasing increasing, feasible, emission non-increasing lpcap* q' *such that* $I^\eta \cdot q' \geq 0$ *if and only if*

$$\left[\gamma^* \neq 0 \textit{ when } X_5 = I^\eta\right] \quad \textit{and} \quad \left[\gamma^* \neq 0 \textit{ when } X_5 = -I^\eta\right].$$

Testing for such hypotheses amounts to first solving problem (4.15) with $X = \begin{bmatrix} \boldsymbol{\chi} & X_5 \end{bmatrix}$ in problem (4.15) with $X_5 = I^\eta$ or $X_5 = -I^\eta$ and then checking for the signs of γ^* and β^*.

Here, we test the following simple hypotheses:

(1) *Existence of efficiency-improving reforms at the status-quo that are also thermal energy-increasing/decreasing.*

In this case, vector $I^{\eta} = \eta^{\mathcal{T}}$, so that an lpcap is thermal energy-increasing (decreasing) if[38]

$$\frac{\dot{\mathcal{T}}}{\bar{e}_T} = \eta^{\mathcal{T}} \cdot q > 0 \qquad \left(\frac{\dot{\mathcal{T}}}{\bar{e}_T} = \eta^{\mathcal{T}} \cdot q < 0 \right)$$

(2) *Existence of efficiency-improving lpcaps at the status-quo that also increase (decrease) usage of coal in the thermal energy sector.*

In this case, vector I^{η} is a 13-dimensional vector with the eighth element being one and all other elements being zero, so that an lpcap results in an increase (decrease) in the coal consumed by thermal power plants if

$$\dot{x}_{TC} = I^{\eta} \cdot q > 0 \qquad (\dot{x}_{TC} = I^{\eta} \cdot q < 0)$$

(3) *Existence of efficiency-improving lpcaps at the status-quo that also increase (decrease) non-electrical energy.*

The total non-electrical energy is the sum of non-electrical energy from coal, gas, and oil. It is given by[39]

$$e_{NE} := e_O + e_{NC} + e_{NG} = \frac{\epsilon_O}{h_O} x_O + \varepsilon_{NC} \epsilon_C x_{NC} + \varepsilon_{NC} \epsilon_G x_{NG}.$$

In this case, vector I^{η} is the vector of partial elasticities of e_{NE} with respect to various active policy variables and is given by

$$I^{\eta} \;\; = \;\; \left\langle 0,\, 0,\, 0,\, 0,\, 0,\, 0,\, 0,\, 0,\, 0,\, \varepsilon_{NC} \frac{\epsilon_C \bar{x}_{NC}}{\bar{e}_{NE}},\, \varepsilon_{NG} \frac{\epsilon_G \bar{x}_{NG}}{\bar{e}_{NE}},\, \frac{\epsilon_O \bar{x}_O}{\bar{e}_{NG}},\, 0 \right\rangle$$

Thus, an lpcap q results in an increase (decrease) in non-electrical energy if

$$\dot{e}_{NC} = I^{\eta} \cdot q > 0 \qquad (\dot{e}_{NE} = I^{\eta} \cdot q < 0)\,.$$

(4) *Existence of efficiency-improving lpcaps at the status-quo that also increase (decrease) usage of renewable energy.*

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[38] $\eta^{\mathcal{T}}$ is as defined in (4.2).

[39] See also Section 4.2.1

Since, the generation of renewable energy is given by[40]

$$e_R = E^R\left(k_R, l_R\right),$$

vector I^η is the vector of partial elasticities of function E^R with respect to various active policy variables and is given by

$$I^\eta = \left\langle 0,\ 0,\ \frac{E_k^R \bar{k}_R}{\bar{e}_R},\ 0,\ 0,\ \frac{E_l^R \bar{l}_R}{\bar{e}_R},\ 0,\ 0,\ 0,\ 0,\ 0,\ 0,\ 0 \right\rangle.$$

Thus, an lpcap q results in an increase (decrease) in renewable energy if

$$\dot{e}_R = I^\eta \cdot q > 0 \qquad \left(\dot{e}_R = I^\eta \cdot q < 0\right)$$

(5) *Existence of efficiency-improving lpcaps at the status-quo that also increase (decrease) afforestation.*

In this case, vector I^η is a 13-dimensional vector with the last element being one and all other elements being zero, so that an lpcap results in an increase (decrease) in afforestation if

$$\dot{a} = I^\eta \cdot q > 0 \qquad \left(\dot{a} = I^\eta \cdot q < 0\right)$$

4.5 Results from Estimation of Production Functions and Government's Forest Expenditure Function

Tables 4.2 to 4.5 below summarise the estimates of various specifications of production functions F, E^C, and E^R that describe the technologies used in intended production. Table 4.6 provides estimate of the government's forest expenditure function.

4.5.1 Comparison of Estimates of Various Specifications of Production Functions in Intended Production

The CES and LVES-2 specifications do not fit data well for all the three production functions E^C, E^R, and F: non-nested CES fits data well for function F, but not for E^C and E^R; while LVES-2 fits data well for F and E^C, but not for E^R. The estimates of

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[40] See Section 4.2.1.

production functions for various functional specifications are provided in Tables 4.2 to 4.5. Looking at the overall fit as indicated by the values of R^2, these tables reveal that the specified forms of the production functions fit the data well. In particular, LVES specifications perform better, *e.g.,* for production function F of sector $\mathcal{Y}$, specification LVES-2 performs best among the four functional specifications (though it is only marginally better than non-nested CES). For production function E^C, LVES-2 again fits data best. Only Cobb Douglas and LVES-1 specifications of function E^R fit data well and, of the two, LVES-1 performs better.

Given these closely performing estimates of the production function based on different functional specifications, the choice of the functional forms for further analyses (such as computing the MACs and testing existence and the structure of efficiency-improving reforms) depends also on the extent to which these various production functions result in technologies that capture the appropriate relations between inputs and outputs in intended production.[41]

The Cobb-Douglas (CD) Specification with Constant Returns to Scale

$$\begin{aligned}
F:\ \ln Y &= A_Y + \beta \ln e + \alpha \ln k_Y + (1-\alpha-\beta)\ln l_Y \implies Y = \exp\left(A_Y\right) e^{\beta} k_Y^{\alpha} l_Y^{1-\alpha-\beta} \\
E^C:\ \ln e_{TC} &= A_{TC} + \beta \ln x_{TC} + \alpha \ln k_{TC} + (1-\alpha-\beta)\ln l_{TC} \implies e_{TC} = \exp\left(A_{TC}\right) x_{TC}^{\beta} k_{TC}^{\alpha} l_{TC}^{1-\alpha-\beta} \\
E^R:\ \ln e_R &= A_R + \alpha \ln k_R + (1-\alpha)\ln l_R \implies e_R = \exp\left(A_R\right) k_R^{\alpha} l_R^{1-\alpha}
\end{aligned}$$

---

[41] Table 4.1 summarised the restrictions imposed on the intended production technologies by these functional forms.

Table 4.2: Estimates of E^C, E^R, and F under CD-CRS Specification

Parameters	**Coefficients** (E^C)	**Coefficients** (E^R)	**Coefficients** (F)
β	0.557***		0.332***
	(0.055)		(0.010)
α	0.261***	0.537***	0.367***
	(0.028)	(0.043)	(0.023)
A_{TC}	-4.389***		
	(0.289)		
A_R		-2.563***	
		(0.086)	
A_Y			0.648***
			(0.111)
N	210	210	210
R^2	0.9304	0.4811	0.9572

Notes (for Tables 2 to 6):
Robust standard errors in brackets.
*** Significant at 1%.
** Significant at 5%.
* Significant at 10%.

The (Non-nested) CES Production Function

CES production function is well-specified only for sector $\mathcal{Y}$. It does not fit data well in the renewable and coal-fired electricity generating sectors.

$$F: \quad Y = [\beta e^{\rho} + \alpha k_Y{}^{\rho} + (1 - \alpha - \beta) l_Y{}^{\rho}]^{\frac{1}{\rho}}.$$

Table 4.3: Estimate of F under Non-nested CES Specification

Parameters	**Coefficients** (KEL)
β	0.340***
	(0.054)
α	0.395***
	(0.043)
ρ	0.279***
	(0.109)
N	210
R^2	0.9777

LVES-1 Specification

$$
\begin{aligned}
F: \quad Y &= \frac{A_Y e^{\beta} {k_Y}^{\alpha} {l_Y}^{\mu-\alpha-\beta}}{1 + {e_Y}^{\beta} + {k_Y}^{\alpha} + {l_Y}^{1-\alpha-\beta}} \\
E^C: \quad e_{TC} &= \frac{A_{TC} {x_{TC}}^{\beta} {k_{TC}}^{\alpha} {l_{TC}}^{1-\beta-\alpha}}{\mu + {x_{TC}}^{\beta} + {k_{TC}}^{\alpha} + {l_{TC}}^{1-\beta-\alpha}} \\
E^R: \quad e_R &= \frac{A_R {k_R}^{\alpha} {l_R}^{1-\alpha}}{\mu + {k_R}^{\alpha} + {l_R}^{1-\alpha}}.
\end{aligned}
$$

In the context of our data, the above production functions can be estimated if μ is fixed as one.

Table 4.4: Estimates of E^C, E^R, and F under LVES-1 Specification

Parameters	**Coefficients** (E^C)	**Coefficients** (E^R)	**Coefficients** (F)
β	0.293**		0.410***
	(0.126)		(0.133)
α	0.413***	0.396***	0.285*
	(0.133)	(0.103)	(0.162)
A_{TC}	1.076***		
	(0.117)		
A_R		1.780***	
		(0.159)	
A_Y			88.631***
			(22.916)
N	210	210	210
R^2	0.9207	0.8417	0.9103

LVES-2 Specification

LVES-2 does not fit the data in the renewable sector well.

$$
\begin{aligned}
F: \quad Y &= \frac{A_Y e^{\beta} {k_Y}^{1-\beta}}{\mu + (\frac{e_Y}{l_Y})^{\beta} + (\frac{k_Y}{l_Y})^{1-\beta}} \\
E^C: \quad e_{TC} &= \frac{A_{TC} {x_{TC}}^{\beta} {k_{TC}}^{1-\beta}}{\mu + (\frac{x_{TC}}{l_{TC}})^{\beta} + (\frac{k_{TC}}{l_{TC}})^{1-\beta}}.
\end{aligned}
$$

Production function E^C is well-specified when μ is fixed equal to one.

Table 4.5: Estimates of E^C and F under LVES-2 Specification

Parameters	**Coefficient** (E^C)	**Coefficient** (F)
β	0.333***	0.144***
	(0.092)	(0.030)
μ		1.456***
		(0.313)
A_{TC}	0.213***	
	(0.022)	
A_Y		2.116***
		(0.383)
N	210	210
R^2	0.9437	0.9778

4.5.2 Forest Expenditure

We found that only a linear specification of the government expenditure function yields statistically significant estimates.[42]

$$\Phi : \quad G^{af} = \beta_0 + \beta_1 a + \beta_2 (a + f).$$

Table 4.6: Estimate of Φ

Parameters	**Coefficients** (Φ)
β_0	2.751***
	(0.564)
β_1	1.77e-05***
	(2.84e-06)
β_2	4.44e-07***
	(8.26e-08)
N	210
R^2	0.4713

4.6 Estimates of Elasticities of Substitution in Intended Production

Based on the estimates of production functions reported in Section 4.5, we compute the pair-wise elasticities of substitution between inputs in intended production for the year 2012 for all provinces. Table 4.7 can be used to compare estimates of these under

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[42] We also tried non-linear specifications such as quadratic, but the estimates were statistically insignificant.

different functional specifications for production functions F and E^C, estimates of which are provided in Section 4.5.

Table 4.7: Pair-wise Elasticities of Substitution between Inputs under Cobb-Douglas, Non-nested CES, LVES-1, and LVES-2 Production Functions

Region	LVES-1 (F)			LVES-2 (F)			LVES-1 (E^C)			LVES-2 (E^C)		
	σ_{ek}	σ_{le}	σ_{lk}	σ_{ek}	σ_{le}	σ_{lk}	σ_{xk}	σ_{lx}	σ_{lk}	σ_{xk}	σ_{lx}	σ_{lk}
Beijing	0.9039	0.8794	0.8161	0.9208	0.8762	0.5613	0.7889	0.9263	0.8636	0.6821	0.9675	0.6649
Tianjin	0.8905	0.8913	0.8217	0.8795	0.9255	0.5535	0.8020	0.8904	0.9032	0.7364	0.9147	0.7510
Hebei	0.8837	0.8801	0.8357	0.8850	0.9211	0.5564	0.7979	0.8839	0.9071	0.7455	0.8965	0.7790
Shanxi	0.8872	0.8730	0.8408	0.9057	0.8983	0.5626	0.7987	0.8750	0.9169	0.7491	0.8841	0.7996
Inner Mongolia	0.8770	0.8853	0.8401	0.8614	0.9392	0.5535	0.7950	0.8802	0.9112	0.7458	0.8911	0.7904
Liaoning	0.8883	0.8831	0.8284	0.8884	0.9178	0.5559	0.7987	0.8862	0.9050	0.7438	0.9011	0.7714
Jilin	0.8867	0.8889	0.8274	0.8761	0.9283	0.5539	0.8070	0.8794	0.9118	0.7526	0.8880	0.7859
Heilongjiang	0.8934	0.8800	0.8283	0.9049	0.8995	0.5597	0.8165	0.8789	0.9013	0.7785	0.8574	0.8063
Shanghai	0.8950	0.8844	0.8209	0.8993	0.9063	0.5567	0.7905	0.9011	0.8952	0.7099	0.9433	0.7152
Jiangsu	0.8878	0.8830	0.8265	0.8853	0.9205	0.5549	0.7960	0.8880	0.9007	0.7474	0.8958	0.7774
Zhejiang	0.8952	0.8802	0.8224	0.9049	0.8996	0.5581	0.7943	0.8903	0.9022	0.7347	0.9135	0.7572
Anhui	0.8937	0.8814	0.8264	0.9028	0.9022	0.5587	0.7981	0.8847	0.9072	0.7426	0.9013	0.7730
Fujian	0.8970	0.8818	0.8213	0.9070	0.8968	0.5586	0.7935	0.8893	0.9091	0.7199	0.9299	0.7393
Jiangxi	0.8977	0.8826	0.8221	0.9082	0.8952	0.5592	0.8048	0.8822	0.9125	0.7424	0.9028	0.7698
Shandong	0.8847	0.8793	0.8331	0.8863	0.9197	0.5560	0.8003	0.8837	0.9034	0.7557	0.8830	0.7914
Henan	0.8904	0.8804	0.8273	0.8962	0.9098	0.5571	0.8021	0.8855	0.9004	0.7580	0.8828	0.7881
Hubei	0.8925	0.8783	0.8292	0.9049	0.8995	0.5598	0.7989	0.8916	0.9023	0.7325	0.9187	0.7473
Hunan	0.8927	0.8816	0.8262	0.9001	0.9053	0.5580	0.7990	0.8899	0.9049	0.7322	0.9181	0.7496
Guangdong	0.8972	0.8769	0.8221	0.9119	0.8901	0.5598	0.7885	0.8989	0.8928	0.7251	0.9268	0.7384
Guangxi	0.8918	0.8869	0.8238	0.8901	0.9160	0.5556	0.8004	0.8872	0.9103	0.7290	0.9207	0.7485
Hainan	0.8979	0.8889	0.8252	0.9030	0.9019	0.5587	0.8146	0.8805	0.9213	0.7385	0.9088	0.7623
Chongqing	0.8948	0.8822	0.8258	0.9041	0.9005	0.5590	0.8076	0.8838	0.9116	0.7421	0.9054	0.7643
Sichuan	0.8933	0.8777	0.8285	0.9068	0.8970	0.5601	0.8048	0.8869	0.9057	0.7434	0.9052	0.7626
Guizhou	0.8948	0.8756	0.8339	0.9152	0.8845	0.5646	0.8047	0.8651	0.9294	0.7512	0.8749	0.8144
Yunnan	0.8943	0.8800	0.8280	0.9067	0.8971	0.5602	0.8020	0.8827	0.9140	0.7356	0.9107	0.7627
Shaanxi	0.8908	0.8807	0.8301	0.8991	0.9066	0.5586	0.8036	0.8851	0.9040	0.7515	0.8928	0.7774
Gansu	0.8980	0.8781	0.8298	0.9170	0.8818	0.5642	0.8051	0.8804	0.9130	0.7464	0.8964	0.7779
Qinghai	0.8893	0.8878	0.8369	0.8901	0.9163	0.5583	0.8098	0.8779	0.9312	0.7211	0.9261	0.7483
Ningxia	0.8852	0.8864	0.8407	0.8838	0.9223	0.5576	0.8034	0.8724	0.9226	0.7465	0.8885	0.7945
Xinjiang	0.8909	0.8787	0.8342	0.9040	0.9006	0.5609	0.8032	0.8756	0.9181	0.7473	0.8902	0.7899

Cobb Douglas: elasticity of substitution is one. Non-nested CES specification for F: elasticity of substitution is 1.3870.

The summary statistics of these elasticities is provided in Table 4.8. These tables show the contrast between the values of elasticities of substitution computed for conventional production functions such as the Cobb Douglas and CES and the LVES specifications proposed in this work.

Table 4.8: Descriptive Statistics of Pair-wise Elasticity of Substitution for LVES-1 and LVES-2

	Obs.	**Mean**	**Median**	**Std. Dev.**	**Min**	**Max**
σ **LVES-1** (F)						
σ_{ek}	30	0.8919	0.8926	0.0053	0.8770	0.9039
σ_{le}	30	0.8818	0.8811	0.0042	0.8730	0.8913
σ_{lk}	30	0.8284	0.8277	0.0062	0.8161	0.8408
σ **LVES-2** (F)						
σ_{ek}	30	0.8983	0.9029	0.0132	0.8614	0.9208
σ_{le}	30	0.9059	0.9021	0.0145	0.8762	0.9392
σ_{lk}	30	0.5584	0.5586	0.0028	0.5535	0.5646
σ **LVES-1** (E^C)						
σ_{xk}	30	0.8010	0.8012	0.0066	0.7885	0.8165
σ_{lx}	30	0.8854	0.8843	0.0106	0.8651	0.9263
σ_{lk}	30	0.9077	0.9072	0.0123	0.8636	0.9312
σ **LVES-2** (E^C)						
σ_{xk}	30	0.7396	0.7430	0.0170	0.6821	0.7785
σ_{lx}	30	0.9045	0.9021	0.0217	0.8574	0.9675
σ_{lk}	30	0.7666	0.7706	0.0294	0.6649	0.8144

It is well known that the elasticity of substitution between any two inputs for Cobb Douglas specification is one, while in the non-nested CES case specified in Section 4.5.1, it is $\frac{1}{1-\rho}$. As noted in Section 4.5, CES functional specification fits our data only for production function F of sector $\mathcal{Y}$. Based on the estimated production function (see Table 3), the constant elasticity of substitution is computed as 1.3870, which is greater than one. Thus, all inputs are highly substitutable under a CES specification of production function F.[43]

On the other hand, Table 4.7 shows that the elasticities of substitution are not constant but vary from data point to data point in the case of LVES specifications. Note that these specifications imply that inputs are highly complementary as the elasticities of substitution take values less than one.[44] The table reveals that there is high complementarity between capital and energy inputs in sector $\mathcal{Y}$ (whose production function is F), with the

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[43] Recall our definition of high substitutability between inputs in Section 4.3.1

[44] Recall our definition of high complementarity between inputs in Section 4.3.1

mean elasticity of substitution (as seen in Table 4.8) being 0.8919 for LVES-1 and 0.8983 for LVES-2. The complementarity between capital and coal inputs is also high in the sector producing coal-fired electricity with production function E^C. The average elasticity of substitution between capital and coal inputs can be observed as 0.8010 for LVES-1 and 0.7396 for LVES-2.

4.7 Results from Estimation of MACs under Different Functional Specifications

Estimates of MACs were obtained using (4.24) after solving problem (4.15) under four different specifications of intended production technologies:

(i) Cobb Douglas specification: We assume that all three production functions F, E^C, and E^R defining intended production have Cobb Douglas form and use estimates in Table 4.2.

(ii) Non-nested CES specification: Recall that the CES specification fits the data only for production function F of sector $\mathcal{Y}$. Hence, we assume that production function F has the CES specification estimated in Table 4.3. We combine this with Cobb Douglas specifications for production functions E^C and E^R in Table 4.2.

(iii) LVES-1 specification: We assume that all three production functions F, E^C, and E^R defining intended production have the LVES-1 form and use estimates in Table 4.4.

(iv) LVES-2 specification: Recall that the LVES-2 specification does not fit the data for production function E^R. Hence, we assume that production function E^R has LVES-1 specification estimated in Table 4.4, while all the remaining production functions, namely, F and E^C, have LVES-2 specification estimated in Table 4.5.

Estimates of MACs under specifications (i) to (iv) above as well as their rankings are presented in Table 4.9, while the rank correlations between estimates of MACs under different functional specifications and their descriptive statistics are presented in Tables 4.10 and 4.11. These tables reveal the high sensitivity of estimates of MACs to the specification of forms for the production functions employed.

Table 4.9: Marginal Abatement Costs under Cobb-Douglas, Non-nested CES, LVES-1, and LVES-2 Specifications of Intended Technology

Region	Cobb-Douglas		CES		LVES-1		LVES-2	
	MAC	Rank	MAC	Rank	MAC	Rank	MAC	Rank
Beijing	1706.37	1	318.60	1	1699.89	1	515.59	1
Tianjin	777.38	5	125.87	2	701.40	7	116.13	4
Hebei	400.40	23	0.00	22	292.10	23	0.00	21
Shanxi	219.64	28	0.00	22	200.10	26	0.00	21
Inner Mongolia	174.67	29	0.00	22	98.10	30	0.00	21
Liaoning	571.29	18	46.68	15	410.03	18	41.04	15
Jilin	636.03	11	66.25	10	662.38	10	77.18	8
Heilongjiang	590.39	16	45.24	16	583.29	12	45.08	13
Shanghai	729.65	6	65.62	11	461.37	16	41.21	14
Jiangsu	539.90	19	58.34	13	195.14	27	17.66	18
Zhejiang	604.83	14	77.66	8	260.39	25	34.59	16
Anhui	479.09	22	32.16	19	339.72	22	0.00	21
Fujian	707.52	9	97.94	5	522.39	14	95.29	7
Jiangxi	798.93	2	115.37	3	818.96	4	140.90	3
Shandong	508.41	21	16.57	21	265.08	24	11.79	20
Henan	609.68	13	64.35	12	350.96	21	52.67	12
Hubei	614.51	12	44.99	17	569.79	13	63.35	10
Hunan	716.10	8	82.22	6	663.48	8	113.20	5
Guangdong	583.05	17	79.06	7	153.09	28	12.61	19
Guangxi	793.32	3	113.58	4	816.47	5	152.73	2
Hainan	791.24	4	0.00	22	1455.83	2	0.00	21
Chongqing	728.04	7	74.54	9	842.25	3	108.00	6
Sichuan	663.51	10	48.40	14	586.68	11	71.86	9
Guizhou	297.37	26	0.00	22	374.50	19	0.00	21
Yunnan	597.60	15	43.35	18	663.38	9	55.13	11
Shaanxi	522.29	20	24.13	20	499.57	15	19.82	17
Gansu	359.74	24	0.00	22	422.44	17	0.00	21
Qinghai	285.81	27	0.00	22	737.86	6	0.00	21
Ningxia	88.40	30	0.00	22	149.23	29	0.00	21
Xinjiang	328.42	25	0.00	22	368.88	20	0.00	21

Unit of measurement of MAC: USD/tC.

The tables indicate that MACs vary widely across functional forms. The mean MAC for the Cobb Douglas specification is 580.78 USD per ton of carbon (USD/tC), while it is much lower (54.70 USD/tc) for the CES specification. For the LVES class, it is higher for LVES-1 specification than for LVES-2 specification. Thus, the Cobb Douglas and LVES-1 specification tend to yield higher levels of MACs as compared to the CES and LVES-2 specifications.

Although the magnitudes of MACs vary a lot depending on the functional specifications employed, Table 4.10 reveals a generally high rank correlation between estimates from different functional specifications. The correlations between rankings of MACs induced by the Cobb Douglas form and other forms is high and so is the correlation between rankings induced by LVES-2 and the other forms.

Table 4.10: Descriptive Statistics of Marginal Abatement Costs under Cobb Douglas, Non-nested CES, LVES-1, and LVES-2 Specifications of Intended Technology

MAC	**Obs.**	**Mean**	**Median**	**Std. Dev.**	**Min**	**Max**
Cobb-Douglas	30	580.78	594.00	287.957	88.4	1706.37
CES	30	54.70	45.96	63.408	0	318.6
LVES-1	30	538.83	480.47	355.448	98.1	1699.89
LVES-2	30	59.53	37.82	97.964	0	515.59

Table 4.11: Spearman's Rank Correlation Coefficients for Marginal Abatement Costs from Cobb Douglas, Non-nested CES, LVES-1, and LVES-2 Specifications of Intended Technology

	Cobb-Douglas	**CES**	**LVES-1**	**LVES-2**
Cobb-Douglas	1.0000			
CES	0.8129**	1.0000		
LVES-1	0.7362**	0.4296**	1.0000	
LVES-2	0.8475**	0.8956**	0.6390**	1.0000

* Significant at 10%.
** Significant at 5%.

Even within a given functional specification, MACs vary a lot between different provinces. As seen in Table 4.11, MACs range from zero to 319 USD/tC for the CES form, from zero to 516 USD/tC for the LVES-2 specification, from 88 to 1706 USD/tc for the Cobb Douglas specification and from 98 to 1699 for the LVES-1 specification. In all the functional specifications, Beijing has the highest MAC. We also find that the rank correlation coefficient between MACs and thermal electricity generation by provinces is negative. For example, for Cobb Douglas and LVES-1 functional forms, it is -0.503 and -0.888, resp. Thus, provinces ranked higher in terms of thermal electricity generation are also provinces with lower MACs.[45] Top generators of thermal electricity include Jiangsu, Shandong, Inner Mongolia, Guangdong, Henan, Shanxi, Zhejiang, and Hebei. MACs of these provinces are among the lowest across all functional forms. Tables 4.9 and 4.10 reveal that the median two provinces are Heilongjiang and Yunnan for the Cobb Douglas specification, Liaoning and Heilongjiang for the CES specification, Shanghai and

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[45] To see province level generation of thermal electricity, see Table 5.4 of Chapter 5.

Shaanxi for the LVES-1 specification, and Liaoning and Zhejiang for the LVES-2 specification. For any functional form, the provinces ranked above (resp., below) the median provinces have higher (resp., lower) MACs than the median.

4.8 Results from Analysing Efficiency-improving Reforms – Existence and the Optimal Reforms

On solving the problem (4.15) with $m = 0$ (which implies $X = \boldsymbol{\chi}$), for every province we obtain the value of Lagrange multiplier γ in the Lagrangian (4.23), evaluated at the optimum of the problem, as γ^*. As discussed in Chapter 3, existence of efficiency-improving reforms at the status-quo of the province boils down to testing whether γ^* is positive.

Table 4.12 reports the value of γ^* for each province. It also reports the optimal reform under LVES-1 for each province, which we computed using the elasticity analogue of the formulae we derived in Chapter 3 .[46]

Table 4.12 clearly shows that for all provinces, γ^* is positive under the LVES-1 form. Thus, our proposed methodology (in the context of both functional forms) suggests the existence of feasible, consumption expenditure increasing, and emission-non decreasing reforms for every province.

Table 4.12 shows that increasing afforestation is not an optimal efficiency-improving strategy in all except one provincial region. In Beijing, the optimal reforms recommends an increase in afforestation.

The optimal efficiency-improving reforms also clearly demonstrate the importance of reduction in coal usage in thermal electricity generation for efficiency improvements in all provinces, *i.e.,* the optimal reform requires a decrease in x_{TC}, and recommends *increases* in thermal electricity in most provinces, with the exception of Hebei, Shanxi, Inner Mon-

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[46] See Remark 2.

Table 4.12: Existence of Efficiency Increasing Reforms and Optimal Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507

golia, and Shangdong (for which it recommends decreases in thermal energy generation). As will be discussed in Chapter 5, these four provinces are the main coal-mining regions in China as well as some of the top electricity generating and consuming regions, with their electricity consumption exceeding their electricity generation.

Optimal reforms under LVES-1 also recommend increases in gas-fired electricity generation (*i.e.,* they recommend increases in x_{TG}). Recall, gas fired electricity generation is assumed to take the form (4.20). As will be discussed in Chapter 5, this is consistent with the current trend whereby, in several provinces, gas-fired electricity generation is replacing coal-fired electricity generation in the wake of environmental concerns (Li, 2015).

Table 4.13 shows the implications of the optimal reform for renewable energy generation, total energy generation, total coal-fired electricity generation, and total non-electrical energy generation. Optimal reforms involve an increase in total energy generation in all provinces. In majority of the provinces, the breakdown of this increase is also similar: a reduction in coal-fired electricity generation is accompanied by increases in renewable energy, non-electrical energy generation, and gas-fired electricity generation. However, exceptions include Beijing, Tianjin, Hainan, Gansu, and Ningxia. These happen to be provinces generating very little coal-fired electricity. In these provinces, the optimal reform under the LVES-1 form recommends increases in all sources of energy.

Thus, the optimal reform under the LVES-1 form seems to capture more details of the observed province-specific features such as levels of thermal electricity generation and coal-mining activities.

4.9 Results from Empirical Testing of Some Hypotheses on the Structures of Efficiency-improving Reforms

A huge volume of results is generated from all four functional forms. For tractability, in this section, we focus only on the results from the LVES-1 functional form.

Table 4.13: Change in Total Energy Induced by the Optimal Reform and Its Decomposition

Region	Δ_E	Δ_{TC}	Δ_R	Δ_{NE}
Beijing	0.1897	0.0073	0.1072	0.2293
Tianjin	0.2827	0.0163	0.0011	0.4113
Hebei	0.2916	-0.0723	0.0099	0.3779
Shanxi	0.3604	-0.0718	0.0111	0.4652
Inner Mongolia	0.4649	-0.0481	0.0081	0.6714
Liaoning	0.2931	-0.0474	0.0265	0.4126
Jilin	0.2501	-0.0263	0.0559	0.3548
Heilongjiang	0.2403	-0.0030	0.0269	0.3365
Shanghai	0.2903	-0.0018	0.0009	0.4190
Jiangsu	0.3778	-0.0258	0.0168	0.6102
Zhejiang	0.3261	-0.0070	0.0551	0.5750
Anhui	0.3757	-0.0203	0.0282	0.6251
Fujian	0.2948	-0.0263	0.0858	0.5175
Jiangxi	0.2712	-0.0130	0.0783	0.4311
Shandong	0.2461	-0.0654	0.0033	0.3116
Henan	0.3326	-0.0398	0.0220	0.5153
Hubei	0.1613	-0.0552	0.1224	0.2029
Hunan	0.2050	-0.0487	0.0995	0.2898
Guangdong	0.2975	-0.0048	0.0632	0.5407
Guangxi	0.2305	-0.0307	0.1333	0.3494
Hainan	0.3066	0.0226	0.0962	0.4804
Chongqing	0.1872	-0.0124	0.1273	0.2345
Sichuan	0.1695	-0.0293	0.1383	0.2058
Guizhou	0.3613	-0.0385	0.0491	0.5340
Yunnan	0.2197	-0.0416	0.1333	0.3100
Shaanxi	0.2580	-0.0434	0.0340	0.3634
Gansu	0.2965	0.0018	0.0874	0.5251
Qinghai	0.2203	-0.0117	0.2656	0.2419
Ningxia	0.3973	0.0047	0.0167	0.6451
Xinjiang	0.3077	-0.0381	0.0354	0.4234

Δ_E: Change in total energy induced by the optimal reform

Δ_{TC}: Change in coal-fired electricity generation induced by the optimal reform

Δ_R: Change in renewable energy induced by the optimal reform

Δ_{NE}: Change in non-electricity energy induced by the optimal reform

All hypotheses (1) to (5) in Section 4.2.2 regarding structures of efficiency improving reforms are tested employing Remark 5. In each of cases (1) to (5), we solve problem (4.15) with $m = 1$, so that $X = \begin{bmatrix} \boldsymbol{\chi} & X_5 \end{bmatrix}$, for both $X_5 = I^\eta$ and $X_5 = -I^\eta$. We then use Remark 5 to test the hypotheses. Table 4.14, below, reports the results for case (1) on existence of efficiency increasing reforms that are also thermal electricity increasing (decreasing) at the status-quos of all provinces. In the Appendix, Tables 4.15 to 4.18 report the results for the remaining four cases.

All the five cases show that part (iii) of Remark 5 is true for all provinces. Values of γ^* when problem (4.15) is solved for both cases $X_5 = I^\eta$ and $X_5 = -I^\eta$ are listed in Tables 4.14 to 4.18. As seen in these tables, γ^* is always positive. Thus, we can conclude that in every province,

(a) there exist efficiency improving reforms that are thermal energy increasing and there also exist efficiency improving reforms that are thermal energy decreasing.

(b) there exist efficiency improving reforms that are consistent with increased usage of coal in thermal power plants, while there are also exist efficiency improving reforms that are consistent with decreased usage of coal in thermal power plants.

(c) there exist efficiency improving reforms that involve increase in non-electrical energy from fossil fuels and there are also exist efficiency improving reforms that involve decrease in non-electrical energy from fossil fuels.

(d) there exist efficiency improving reforms that promote renewable energy generation, while efficiency improving reforms which discourage renewable energy generation also exist.

(e) there exist efficiency improving reforms that recommend increases in afforestation and there exist efficiency improving reforms that recommend decreases in afforestation.

Thus, the nature of inefficiency at the status-quo of every province is such that efficiency

Table 4.14: Optimal Efficiency-improving and Thermal Electrical Energy-based Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*	β_5
Thermal Energy Non-decreasing Reform															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296	0.0000
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0000
Hebei	-0.0046	0.2149	0.0031	-0.0016	0.2429	0.0183	0.0000	-0.8591	0.0000	0.3937	0.0323	-0.0037	-0.0182	0.0416	0.0085
Shanxi	-0.0064	0.1827	0.0065	-0.0017	0.2138	0.0221	0.0000	-0.8335	0.0052	0.4743	0.0158	-0.0002	-0.0184	0.0590	0.0221
Inner Mongolia	-0.0069	0.1573	0.0063	-0.0034	0.1771	0.0154	0.0000	-0.6646	0.0017	0.7068	0.0253	-0.0014	-0.0404	0.0836	0.0004
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491	0.0000
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506	0.0000
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528	0.0000
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536	0.0000
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466	0.0000
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736	0.0000
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508	0.0000
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537	0.0000
Shandong	-0.0035	0.2192	0.0009	-0.0017	0.2302	0.0056	0.0000	-0.8169	0.0016	0.4448	0.0349	-0.1803	-0.0087	0.0400	0.0053
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562	0.0000
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279	0.0000
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358	0.0000
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407	0.0000
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425	0.0000
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649	0.0000
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342	0.0000
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246	0.0000
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650	0.0000
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388	0.0000
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499	0.0000
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579	0.0000
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350	0.0000
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730	0.0000
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507	0.0000
Thermal Energy Non-increasing Reform															
Beijing	-0.0041	0.0976	0.0251	-0.0003	0.3172	0.2208	0.0000	-0.4812	-0.1090	-0.1734	0.7499	0.0683	0.0028	0.0267	0.0764
Tianjin	-0.0038	0.1824	0.0003	-0.0010	0.2069	0.0018	0.0000	-0.6813	-0.0005	0.6192	0.2583	0.0981	-0.0003	0.0515	0.1055
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416	0.0000
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591	0.0000
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836	0.0000
Liaoning	-0.0041	0.2025	0.0199	-0.0012	0.2267	0.0538	0.0000	-0.7834	0.0012	0.5263	0.1150	0.0117	-0.0122	0.0490	0.0167
Jilin	-0.0034	0.2237	0.0503	-0.0017	0.2152	0.1173	0.0000	-0.8479	0.0000	0.4026	0.0798	0.0054	-0.0014	0.0501	0.0364
Heilongjiang	-0.0063	0.2534	0.0222	-0.0048	0.2241	0.0537	0.0000	-0.8362	0.0000	0.4178	0.0907	0.0074	-0.0084	0.0513	0.0667
Shanghai	-0.0035	0.1261	0.0002	-0.0003	0.2078	0.0015	0.0000	-0.5628	0.0139	0.5998	0.2411	0.4541	-0.0001	0.0380	0.0816
Jiangsu	-0.0033	0.1588	0.0132	-0.0012	0.1837	0.0342	0.0000	-0.6138	0.0178	0.7428	0.1035	0.0081	-0.0024	0.0532	0.0400
Zhejiang	-0.0032	0.1361	0.0422	-0.0006	0.1784	0.1242	0.0000	-0.5679	0.0154	0.7743	0.0571	0.0822	-0.0026	0.0454	0.0618
Anhui	-0.0054	0.1577	0.0199	-0.0012	0.1894	0.0574	0.0000	-0.6490	0.0000	0.7134	0.0730	0.0022	-0.0022	0.0728	0.0615
Fujian	-0.0039	0.1550	0.1130	-0.0007	0.1916	0.1906	0.0000	-0.6713	0.0223	0.6548	0.0586	0.0826	-0.0054	0.0503	0.0447
Jiangxi	-0.0037	0.1995	0.0918	-0.0008	0.2097	0.1673	0.0000	-0.7887	0.0000	0.5037	0.0621	0.0157	-0.0054	0.0527	0.0560
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0000
Henan	-0.0047	0.2057	0.0245	-0.0022	0.2198	0.0466	0.0000	-0.7467	0.0042	0.5843	0.0868	0.0003	-0.0088	0.0560	0.0271
Hubei	-0.0058	0.2125	0.0560	-0.0018	0.2742	0.3118	0.0000	-0.8504	0.0006	0.2251	0.0713	-0.0075	-0.0147	0.0278	0.0128
Hunan	-0.0056	0.2150	0.1442	-0.0016	0.2552	0.2238	0.0000	-0.8424	0.0000	0.3220	0.0623	0.0058	-0.0219	0.0357	0.0179
Guangdong	-0.0034	0.0934	0.0562	-0.0006	0.1793	0.1540	0.0000	-0.4758	0.0303	0.8223	0.1408	0.0943	-0.0066	0.0389	0.0732
Guangxi	-0.0052	0.2024	0.1614	-0.0018	0.2237	0.3014	0.0000	-0.7998	0.0000	0.3895	0.0177	0.0192	-0.0065	0.0421	0.0317
Hainan	-0.0028	0.1522	0.0779	-0.0006	0.1537	0.1850	0.0000	-0.6095	-0.0174	0.0495	0.7311	0.0650	0.0006	0.0623	0.0997
Chongqing	-0.0039	0.1994	0.1236	-0.0012	0.2135	0.2856	0.0000	-0.7774	0.0000	0.1966	0.4178	0.0029	-0.0110	0.0335	0.0353
Sichuan	-0.0083	0.1928	0.1887	-0.0035	0.2229	0.3449	0.0000	-0.7459	-0.0006	0.1341	0.4290	-0.0060	-0.0088	0.0244	0.0180
Guizhou	-0.0043	0.1657	0.0534	-0.0012	0.1641	0.1130	0.0000	-0.7940	0.0000	0.5471	0.0130	0.0001	-0.0105	0.0650	0.0077
Yunnan	-0.0055	0.2004	0.0534	-0.0017	0.2244	0.3252	0.0000	-0.8328	0.0000	0.3253	0.0170	0.0003	-0.0345	0.0387	0.0175
Shaanxi	-0.0061	0.2192	0.0246	-0.0021	0.2454	0.0699	0.0000	-0.8333	0.0006	0.4146	0.1403	0.0000	-0.0180	0.0497	0.0267
Gansu	-0.0077	0.1500	0.0814	-0.0020	0.1939	0.2024	0.0000	-0.6676	0.0000	0.6559	0.1267	0.0040	-0.0175	0.0561	0.0782
Qinghai	-0.0162	0.1170	0.2144	-0.0131	0.1353	0.6363	0.0000	-0.5609	-0.0059	0.1151	0.4340	0.0001	-0.0214	0.0348	0.0228
Ningxia	-0.0067	0.1163	0.0101	-0.0027	0.1478	0.0295	0.0000	-0.5768	0.0008	0.7874	0.1039	0.0043	-0.0145	0.0714	0.0818
Xinjiang	-0.0045	0.1785	0.0256	-0.0011	0.1964	0.0732	0.0000	-0.7817	0.0010	0.4966	0.2560	-0.0001	-0.0173	0.0506	0.0174

improvements are possible in several ways. Some of these like decreasing fossil-fuel intensive thermal electricity generation or increasing afforestation or switching to renewable energy agree with out intuition, while others like increasing thermal electricity generation or decreasing afforestation or decreasing renewable energy do not. The latter counter-intuitive options are possible because each is combined with changes in other policy variables that can offset its effect on emission. For example, increasing thermal electricity generation may involve substituting less emission-intensive gas-fired electricity generation for more emission-intensive coal-fired electricity generation.

When we solve problem (4.15) for cases (1) to (5), we also obtain the optimal reforms corresponding to $X_5 = I^\eta$ and $X_5 = -I^\eta$. Tables 4.15 to 4.18 list the optimal reforms for each province. Here we discuss the optimal reforms for case (1). The optimal reforms for the other four cases can be similarly explained.

Solving problem (4.15) for case (1) with $X_5 = -I^\eta$ amounts to searching for a feasible, emission non-increasing, and thermal energy non-decreasing reform that increases consumption expenditure the most.

Recall, the optimal efficiency-improving reform discussed in Section 4.8 was obtained from solving problem (4.15) with $X = \boldsymbol{\chi}$. Table 4.12 for LVES-1 showed that, for most provinces, the optimal efficiency improving reforms recommended an increase in thermal energy. Only for the four big coal-mining provinces of Heibei, Shanxi, Inner Mongolia, and Shangdong did they recommend a decrease in thermal energy generation. Thus, for all provinces, excluding these four, the optimal efficiency-improving reform is also the optimal efficiency-improving reform that does not result in a decrease in thermal energy. This can be verified by noting that the reforms corresponding to these provinces in Table 4.12 and in the top part of Table 4.14 are the same. Thus, the optimal reforms q^* solves $-I^\eta \cdot q^* < 0$. From the Kuhn-Tucker first-order conditions, this implies that the Lagrange mutliplier of this constraint is zero. Table 4.14 shows that, for these provinces, $\beta_5^* = 0$.

For Heibei, Shanxi, Inner Mongolia, and Shangdong, the optimal reform that solves problem (4.15) for case (1) with $X_5 = -I^\eta$ recommends no change in thermal electricity generation. Thus, it solves $-I^\eta \cdot q^* = 0$. Thus, the constraint on thermal electricity generation is binding for these provinces and so $\beta_5^* > 0$.

Table 4.14 shows that the reverse is true of the optimal reforms when $X_5 = I^\eta$, that is when we solve to find the optimal efficiency-improving reform that does not result in an increase in thermal electricity generation.

4.10 Conclusions

In this chapter, we applied the methodology developed in Chapter 3 for testing existence and studying the structure of efficiency-improving reforms and for measuring MACs to data on thirty Chinese provinces. To implement the methodology in a manner that is independent of the units in which policy variables are measured, we first converted the the model in Chapter 3 into its elasticity analogue and redefine policy reforms as local proportional changes in the policy variables.

Appropriate production functions need to be specified to estimate energy using and energy generating technologies in the intended output producing sectors. Here, we identify three key features of inputs such as energy employed in the energy using sector $\mathcal{Y}$ and coal employed in the coal-fired electricity generating sector. Firstly, energy and coal are essential inputs into production of intended outputs of sector $\mathcal{Y}$ and coal-fired electricity generating plants, resp. Secondly, in these sectors, inputs such as coal and energy are limitational. For example, it is not possible for coal-fired power plants to generate increasing amounts of electricity by increasing inputs of capital and labour, when the amount of coal is held fixed, and vice-versa. Lastly, there is high complementarity between usage of coal and other inputs in the coal-fired electricity generation. Similarly, there is high complementarity between the energy input and other inputs in the production of intended output in sector $\mathcal{Y}$.

Conventional production functions such as Cobb Douglas and CES do not have all the features mentioned above. We propose a new class of LVES production functions and propose two functions in this class that have these properties. All four functional specifications are estimated using the data. We find that our results on measurement of MACs and efficiency-improving reforms are sensitive to the functional forms used. Under all functional specifications, MACs vary widely across all provinces, with Beijing having the highest MAC. The rank correlation between MACs and thermal electricity generation is negative, indicating that provinces ranking high in thermal electricity generation tend to have lower MACs. These include Jiangsu, Shangdong, Inner Mongolia, Guangdong, Henan, Shanxi, Zhejiang, and Hebei. Many of these provinces such as Inner Mongolia, Guangdong, and Zhejiang also happen to be the largest coal-mining and most industrialised regions in China consuming also the highest amounts of electricity. The wide province-level differences in MACs can be exploited by the Chinese government to meet its emission-reduction targets with least loss in consumption by shifting, in a big way, the onus of emission-reduction to the provinces generating high amounts of thermal energy, as these are the regions where currently the MACs are low.

We also show that efficiency-improving reforms exist for every province and that the optimal efficiency-improving reform is also sensitive to the functional form adopted. In particular, the optimal reforms obtained under the LVES-1 form are more nuanced and relate more to province-specific features. For provinces that are intensively mining coal, the optimal reforms recommend decreasing thermal energy generation, while for all other provinces, they allow increases in thermal energy generation. In general, except for Beijing, they show the limited scope of afforestation in achieving optimal efficiency-improvements. They demonstrate that the efficiency will increase the most when all provinces increase generation of renewable energy and switch from coal-fired electricity generation to gas-fired electricity generation in the thermal energy sector.

Finally, we also study various other hypotheses about efficiency-improving reforms (not necessarily the optimal efficiency-improving reforms). We find that efficiency improvements can be achieved by all provinces in several ways, including both decrease or increase in (i) thermal energy generation, (ii) the levels of afforestation, (iii) renewable energy generation, (iv) the usage of coal in thermal power plants, and (v) non-electrical energy usage.

The next chapter (Chapter 5) studies the regional variations in electricity generation and consumption, renewable resources, primary energy usage, and forest cover in China. Given these regional differences, it analyses the efficiency-improving reforms computed in this chapter for each province and compares the recommendations of these reforms with current governmental policies in place in the province.

Appendix

Checking Concavity of LVES-2

Consider the case of $n = 3$ in LVES-2. In the proof process, Let $A = 1$, $x_1 = l$, $x_2 = e$, $x_3 = k$, and $\theta_1 = \gamma$, $\theta_2 = \beta$, $\theta_3 = \alpha$. Hence, the explicit function form for LVES-2 can be expressed as:

$$y = \frac{e^{\beta}k^{\alpha}}{\mu + (\frac{e}{l})^{\beta} + (\frac{k}{l})^{\alpha}}$$

Proof. For checking the concavity, the Hessian matrix for our new function form can be displayed as

$$H = \begin{bmatrix} \frac{\partial^2 y}{\partial e^2} & \frac{\partial^2 y}{\partial e \partial k} & \frac{\partial^2 y}{\partial e \partial l} \\ \\ \frac{\partial^2 y}{\partial k \partial e} & \frac{\partial^2 y}{\partial k^2} & \frac{\partial^2 y}{\partial k \partial l} \\ \\ \frac{\partial^2 y}{\partial l \partial e} & \frac{\partial^2 y}{\partial l \partial k} & \frac{\partial^2 y}{\partial l^2} \end{bmatrix}$$

(1) The first leading principal minor is $D_1 = \frac{\partial^2 y}{\partial e^2} < 0$.

(2) The second leading principal minor D_2 is

$$D_2 = \frac{-\alpha\beta e^{2\beta-2}k^{2\alpha-2}\left(\begin{array}{l}(\alpha+\beta-1)\mu^3 + (-2+2\alpha+\alpha\beta)\mu^2(\dfrac{e}{l})^{\beta} + (-2+2\beta+\alpha\beta)\mu^2(\dfrac{k}{l})^{\alpha} \\ +(\alpha-1)(1+\beta)\mu(\dfrac{e}{l})^{2\beta} + (\beta-1)(1+\alpha)\mu(\dfrac{k}{l})^{2\alpha} + (\alpha-1)(1+\beta)(\dfrac{e}{l})^{2\beta}(\dfrac{k}{l})^{\alpha} \\ +(\beta-1)(1+\alpha)(\dfrac{e}{l})^{\beta}(\dfrac{k}{l})^{2\alpha} + (\alpha+\beta+\alpha\beta-3)\mu(\dfrac{e}{l})^{\beta}(\dfrac{k}{l})^{\alpha}\end{array}\right)}{\left(\mu + (\frac{e}{l})^{\beta} + (\frac{k}{l})^{\alpha}\right)^5}$$

For checking the sign of D_2, $\alpha \in [0, 1]$ and $\beta \in [0, 1]$, if $\alpha + \beta < 1$, we can get

$-2+2\alpha+\alpha\beta < -2+2\alpha+\alpha(1-\alpha) = (\alpha-1)(2-\alpha) < 0$, and $-2+2\beta+\alpha\beta < -2+2\beta+(1-\beta)\beta = (\beta-1)(2-\beta) < 0$. Furthermore, we also can get $\alpha+\beta+\alpha\beta-3 < 0$. Therefore, the numerator of D_2 is positive and the sign of D_2 is also positive, when $\alpha+\beta < 1$.

(3) Let the determinant of Hessian matrix $D_3 = det(H)$ be the third leading principal minor ,

$$D_3 = \frac{\alpha\beta e^{3\beta-2}k^{3\alpha-2}(\alpha+\beta-1)\begin{pmatrix} \alpha^2(\frac{e}{l})^{\beta}(\frac{k}{l})^{2\alpha} + \beta^2(\frac{e}{l})^{2\beta}(\frac{k}{l})^{\alpha} + \beta^2\mu(\frac{e}{l})^{2\beta} + \beta^2\mu^2(\frac{e}{l})^{\beta} + \alpha^2\mu(\frac{k}{l})^{2\alpha} \\ + \alpha^2\mu^2(\frac{k}{l})^{\alpha} + \alpha(\frac{e}{l})^{\beta}(\frac{k}{l})^{2\alpha} + \beta(\frac{e}{l})^{2\beta}(\frac{k}{l})^{\alpha} + \beta\mu(\frac{e}{l})^{2\beta} + \beta\mu^2(\frac{e}{l})^{\beta} \\ + \alpha\mu(\frac{k}{l})^{2\alpha} + \alpha\mu^2(\frac{k}{l})^{\alpha} + \alpha^2\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} + \beta^2\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} \\ + \alpha\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} + \beta\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} + \alpha\beta^2\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} + \alpha^2\beta\mu(\frac{e}{l})^{\beta}(\frac{k}{l})^{\alpha} \end{pmatrix}}{l^2\left(\mu+(\frac{e}{l})^{\beta}+(\frac{k}{l})^{\alpha}\right)^6}$$

Suppose $\beta \in [0,1]$, $\alpha \in [0,1]$, and $\alpha+\beta \leq 1$. Then the determinant of Hessian matrix is non-negative, *i.e.,* $D_3 \geq 0$. Note $D_1 < 0$ and $D_2 > 0$ as $\alpha+\beta \leq 1$. Hence, LVES-2 is concave. If $\alpha+\beta < 1$ then it is strictly concave.

Table 4.15: Efficiency-improving Thermal Coal-based Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*	β_5
Non-decreasing Reforms															
Beijing	-0.0121	0.2966	0.0235	-0.0005	0.5775	0.2074	0.1922	0.0000	-0.0091	-0.3149	0.6291	0.0529	0.0036	0.0284	0.0177
Tianjin	-0.0127	0.6158	0.0005	-0.0031	0.6527	0.0028	0.3321	0.0000	0.0013	-0.0405	0.2755	0.0825	0.0001	0.0330	0.1218
Hebei	-0.0129	0.6000	0.0113	-0.0045	0.7085	0.0679	0.3487	0.0000	0.0000	-0.0022	0.0861	-0.0162	-0.0616	0.0112	0.0888
Shanxi	-0.0194	0.5561	0.0327	-0.0060	0.7389	0.1113	0.3496	0.0000	0.0034	-0.0010	0.0412	-0.0012	-0.0832	0.0117	0.1341
Inner Mongolia	-0.0265	0.6047	0.0283	-0.0133	0.6958	0.0688	0.3490	0.0000	0.0012	-0.0027	0.0442	-0.0109	-0.1414	0.0187	0.2388
Liaoning	-0.0123	0.6008	0.0553	-0.0036	0.6677	0.1499	0.3345	0.0000	0.0011	-0.0110	0.2277	-0.0559	-0.0245	0.0176	0.1115
Jilin	-0.0096	0.6394	0.1134	-0.0046	0.6093	0.2643	0.3386	0.0000	0.0002	-0.0050	0.1498	0.0058	-0.0023	0.0222	0.1014
Heilongjiang	-0.0171	0.6911	0.0401	-0.0132	0.6111	0.0971	0.3456	0.0000	0.0000	-0.0054	0.1337	0.0008	-0.0114	0.0284	0.1004
Shanghai	-0.0147	0.5305	0.0004	-0.0011	0.7028	0.0026	0.2837	0.0000	0.0157	-0.1496	0.2279	0.2634	0.0000	0.0229	0.1109
Jiangsu	-0.0128	0.6191	0.0368	-0.0046	0.6900	0.0951	0.3234	0.0000	0.0165	-0.0101	0.1572	-0.0180	-0.0039	0.0191	0.1585
Zhejiang	-0.0131	0.5846	0.0927	-0.0021	0.6858	0.2731	0.3122	0.0000	0.0190	-0.0065	0.0722	0.0376	-0.0021	0.0206	0.1422
Anhui	-0.0209	0.6085	0.0515	-0.0045	0.6868	0.1485	0.3453	0.0000	0.0000	-0.0046	0.1166	0.0012	-0.0025	0.0282	0.2034
Fujian	-0.0123	0.5265	0.2569	-0.0018	0.6134	0.4335	0.2760	0.0000	0.0273	-0.0103	0.0891	0.0871	-0.0025	0.0221	0.1288
Jiangxi	-0.0108	0.6028	0.1833	-0.0022	0.6109	0.3340	0.3292	0.0000	0.0000	-0.0028	0.0973	0.0203	-0.0014	0.0264	0.1118
Shandong	-0.0079	0.4954	0.0026	-0.0040	0.5302	0.0158	0.2697	0.0000	0.0010	0.0600	0.0666	-0.6260	-0.0219	0.0142	0.0850
Henan	-0.0143	0.6316	0.0656	-0.0065	0.6669	0.1246	0.3348	0.0000	0.0040	-0.0078	0.1542	-0.0015	-0.0164	0.0209	0.1335
Hubei	-0.0121	0.4553	0.1080	-0.0036	0.5750	0.6008	0.2685	0.0000	0.0018	-0.0029	0.1271	-0.0200	-0.0265	0.0144	0.0499
Hunan	-0.0125	0.5045	0.2978	-0.0035	0.5879	0.4619	0.2891	0.0000	0.0000	-0.0032	0.1128	0.0048	-0.0366	0.0173	0.0678
Guangdong	-0.0170	0.5173	0.1103	-0.0020	0.7233	0.3025	0.2872	0.0000	0.0372	-0.0176	0.1443	0.0130	-0.0051	0.0198	0.1437
Guangxi	-0.0114	0.4909	0.2997	-0.0036	0.5285	0.5597	0.2741	0.0000	0.0000	-0.0006	0.0277	0.0243	-0.0058	0.0227	0.0807
Hainan	-0.0091	0.5161	0.1221	-0.0016	0.4889	0.2899	0.2660	0.0000	-0.0473	-0.4716	0.3162	-0.0013	0.0095	0.0398	0.1490
Chongqing	-0.0077	0.4449	0.1830	-0.0021	0.4564	0.4229	0.2439	0.0000	0.0000	-0.0864	0.5606	0.0032	-0.0120	0.0227	0.0544
Sichuan	-0.0130	0.3676	0.2729	-0.0052	0.4080	0.4989	0.2048	0.0000	0.0007	-0.1017	0.5676	-0.0124	-0.0117	0.0168	0.0375
Guizhou	-0.0152	0.5808	0.1980	-0.0043	0.5794	0.4193	0.3314	0.0000	0.0000	-0.0004	0.0334	-0.0014	-0.0282	0.0175	0.1527
Yunnan	-0.0121	0.4633	0.1088	-0.0036	0.5096	0.6631	0.2645	0.0000	0.0000	-0.0014	0.0302	0.0003	-0.0559	0.0190	0.0732
Shaanxi	-0.0166	0.5980	0.0580	-0.0055	0.6567	0.1648	0.3304	0.0000	0.0011	-0.0181	0.2637	0.0000	-0.0339	0.0211	0.1023
Gansu	-0.0257	0.5605	0.1529	-0.0054	0.6240	0.3809	0.3214	0.0000	0.0000	-0.0106	0.1542	0.0022	-0.0140	0.0298	0.1407
Qinghai	-0.0209	0.2214	0.2609	-0.0160	0.2356	0.7744	0.1240	0.0000	0.0009	-0.1417	0.4373	0.0000	-0.0177	0.0286	0.0444
Ningxia	-0.0361	0.6240	0.0259	-0.0121	0.6731	0.0759	0.3606	0.0000	0.0009	-0.0089	0.1381	-0.0081	-0.0212	0.0278	0.2301
Xinjiang	-0.0135	0.5360	0.0701	-0.0033	0.5810	0.2003	0.3062	0.0000	0.0008	-0.0744	0.4789	-0.0028	-0.0354	0.0185	0.1146
Non-increasing Reforms															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296	0.0000
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0000
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416	0.0000
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591	0.0000
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836	0.0000
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491	0.0000
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506	0.0000
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528	0.0000
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536	0.0000
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466	0.0000
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736	0.0000
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508	0.0000
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537	0.0000
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0000
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562	0.0000
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279	0.0000
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358	0.0000
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407	0.0000
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425	0.0000
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649	0.0000
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342	0.0000
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246	0.0000
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650	0.0000
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388	0.0000
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499	0.0000
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579	0.0000
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350	0.0000
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730	0.0000
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507	0.0000

Table 4.16: Efficiency-improving and Non-electrical Energy-based Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*	β_5
Non-decreasing reforms.															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296	0.0000
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0000
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416	0.0000
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591	0.0000
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836	0.0000
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491	0.0000
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506	0.0000
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528	0.0000
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536	0.0000
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466	0.0000
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736	0.0000
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508	0.0000
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537	0.0000
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0000
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562	0.0000
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279	0.0000
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358	0.0000
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407	0.0000
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425	0.0000
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649	0.0000
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342	0.0000
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246	0.0000
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650	0.0000
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388	0.0000
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499	0.0000
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579	0.0000
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350	0.0000
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730	0.0000
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507	0.0000
Non-increasing reforms															
Beijing	-0.0159	0.3877	0.0314	-0.0006	0.7594	0.2766	0.3001	0.1724	0.1709	-0.1562	0.1412	-0.0437	-0.0046	0.0213	0.1244
Tianjin	-0.0132	0.6401	0.0005	-0.0032	0.6784	0.0029	0.3430	-0.0155	0.0139	0.0254	-0.0265	-0.1024	-0.0010	0.0318	0.1770
Hebei	-0.0105	0.4889	0.0088	-0.0037	0.5732	0.0530	0.1960	-0.6130	0.0000	0.0054	-0.0984	-0.0264	-0.0701	0.0144	0.1631
Shanxi	-0.0114	0.3254	0.0176	-0.0034	0.4218	0.0599	0.0945	-0.8340	0.0134	0.0023	-0.0619	-0.0011	-0.0600	0.0218	0.1771
Inner Mongolia	-0.0152	0.3456	0.0149	-0.0075	0.3928	0.0362	0.0849	-0.8392	0.0047	0.0024	-0.0456	-0.0108	-0.1038	0.0355	0.1762
Liaoning	-0.0113	0.5540	0.0502	-0.0033	0.6147	0.1361	0.2725	-0.2476	0.0086	0.0704	-0.1044	-0.3746	-0.0469	0.0194	0.1890
Jilin	-0.0097	0.6460	0.1143	-0.0046	0.6155	0.2664	0.3358	-0.0448	0.0024	0.0050	-0.0560	-0.0420	-0.0073	0.0221	0.2270
Heilongjiang	-0.0172	0.6941	0.0402	-0.0132	0.6137	0.0975	0.3456	-0.0097	0.0000	0.0082	-0.0516	-0.0828	-0.0287	0.0283	0.2237
Shanghai	-0.0141	0.5078	0.0004	-0.0010	0.6731	0.0025	0.2806	-0.1270	0.2469	0.2511	0.0577	-0.2582	-0.0002	0.0239	0.1252
Jiangsu	-0.0117	0.5690	0.0332	-0.0043	0.6329	0.0856	0.2441	-0.4225	0.1161	0.0166	-0.0828	-0.0917	-0.0070	0.0212	0.1359
Zhejiang	-0.0125	0.5586	0.0880	-0.0020	0.6548	0.2595	0.2840	-0.1669	0.1452	0.0483	-0.0217	-0.2271	-0.0066	0.0217	0.1219
Anhui	-0.0208	0.6052	0.0506	-0.0044	0.6820	0.1460	0.3132	-0.2103	0.0000	0.0040	-0.0430	-0.0095	-0.0078	0.0286	0.1896
Fujian	-0.0118	0.5057	0.2480	-0.0017	0.5896	0.4184	0.2765	-0.0639	0.2117	0.0313	-0.0212	-0.1811	-0.0205	0.0229	0.1549
Jiangxi	-0.0109	0.6051	0.1840	-0.0022	0.6132	0.3352	0.3301	-0.0024	0.0000	0.0021	-0.0201	-0.0329	-0.0326	0.0263	0.1896
Shandong	-0.0052	0.3226	0.0016	-0.0026	0.3439	0.0099	0.1206	-0.3776	0.0043	0.1882	-0.0506	-0.7629	-0.0197	0.0227	0.1593
Henan	-0.0141	0.6214	0.0636	-0.0064	0.6554	0.1208	0.2904	-0.2671	0.0323	0.0101	-0.0868	-0.0089	-0.0322	0.0216	0.1721
Hubei	-0.0121	0.4542	0.1073	-0.0035	0.5731	0.5969	0.2597	-0.0541	0.0146	0.0083	-0.0713	-0.1363	-0.0542	0.0145	0.1964
Hunan	-0.0125	0.5042	0.2971	-0.0035	0.5874	0.4608	0.2849	-0.0278	0.0000	0.0045	-0.0459	-0.0739	-0.1019	0.0173	0.1878
Guangdong	-0.0157	0.4791	0.1020	-0.0019	0.6697	0.2798	0.2627	-0.1966	0.2486	0.0698	-0.0429	-0.2379	-0.0132	0.0214	0.1047
Guangxi	-0.0114	0.4902	0.2992	-0.0036	0.5277	0.5587	0.2731	-0.0035	0.0000	0.0024	-0.0071	-0.0584	-0.0369	0.0227	0.1740
Hainan	-0.0110	0.6235	0.1478	-0.0019	0.5908	0.3510	0.3267	-0.0058	0.0802	0.0019	0.0074	-0.0612	-0.0069	0.0329	0.2010
Chongqing	-0.0093	0.5362	0.2195	-0.0025	0.5498	0.5072	0.2833	-0.0734	0.0000	0.0418	-0.1156	-0.0130	-0.0611	0.0189	0.2026
Sichuan	-0.0153	0.4358	0.3189	-0.0061	0.4828	0.5830	0.2163	-0.1787	0.0079	0.0880	-0.2034	-0.0802	-0.0271	0.0144	0.1569
Guizhou	-0.0132	0.5098	0.1682	-0.0038	0.5064	0.3563	0.2283	-0.5229	0.0000	0.0003	-0.0167	-0.0073	-0.0482	0.0206	0.1935
Yunnan	-0.0119	0.4596	0.1074	-0.0036	0.5053	0.6544	0.2524	-0.0716	0.0000	0.0002	-0.0120	-0.0036	-0.1565	0.0192	0.1828
Shaanxi	-0.0169	0.6117	0.0589	-0.0057	0.6712	0.1674	0.3199	-0.1227	0.0094	0.0223	-0.1414	-0.0001	-0.0741	0.0207	0.2189
Gansu	-0.0260	0.5667	0.1542	-0.0055	0.6307	0.3840	0.3185	-0.0459	0.0000	0.0087	-0.0540	-0.0123	-0.0497	0.0296	0.1606
Qinghai	-0.0233	0.2483	0.2901	-0.0178	0.2639	0.8611	0.1303	-0.0869	0.0381	0.0640	-0.0846	-0.0004	-0.0706	0.0257	0.1338
Ningxia	-0.0330	0.5700	0.0230	-0.0110	0.6121	0.0675	0.2702	-0.4611	0.0073	0.0118	-0.0736	-0.0386	-0.0373	0.0312	0.1696
Xinjiang	-0.0138	0.5487	0.0702	-0.0034	0.5928	0.2006	0.2643	-0.3700	0.0086	0.1025	-0.2828	-0.0121	-0.0685	0.0184	0.1917

Table 4.17: Efficiency-improving Renewable Energy-based Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*	β_5
Non-decreasing Reforms															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296	0.0000
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0000
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416	0.0000
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591	0.0000
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836	0.0000
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491	0.0000
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506	0.0000
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528	0.0000
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536	0.0000
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466	0.0000
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736	0.0000
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508	0.0000
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537	0.0000
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0000
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562	0.0000
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279	0.0000
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358	0.0000
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407	0.0000
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425	0.0000
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649	0.0000
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342	0.0000
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246	0.0000
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650	0.0000
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388	0.0000
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499	0.0000
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579	0.0000
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350	0.0000
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730	0.0000
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507	0.0000
Non-increasing Reforms															
Beijing	-0.0119	0.2980	-0.0200	-0.0004	0.5759	0.0043	0.1472	-0.2657	0.0054	-0.2261	0.6574	0.0580	0.0030	0.0290	0.0220
Tianjin	-0.0081	0.3907	-0.0002	-0.0019	0.4128	0.0001	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0003
Hebei	-0.0041	0.1909	-0.0020	-0.0014	0.2195	0.0006	-0.0141	-0.8690	0.0000	0.3983	0.0324	-0.0037	-0.0182	0.0416	0.0028
Shanxi	-0.0048	0.1369	-0.0024	-0.0014	0.1712	0.0010	-0.0258	-0.8474	0.0031	0.4822	0.0159	-0.0002	-0.0184	0.0591	0.0056
Inner Mongolia	-0.0069	0.1568	-0.0006	-0.0034	0.1766	0.0003	-0.0003	-0.6649	0.0017	0.7070	0.0253	-0.0014	-0.0404	0.0835	0.0057
Liaoning	-0.0049	0.2417	-0.0026	-0.0014	0.2653	0.0011	0.0227	-0.7686	0.0019	0.5163	0.1143	0.0111	-0.0121	0.0490	0.0121
Jilin	-0.0044	0.3114	-0.0046	-0.0020	0.2958	0.0022	0.0508	-0.8113	0.0004	0.3851	0.0791	0.0053	-0.0014	0.0502	0.0289
Heilongjiang	-0.0099	0.4000	-0.0018	-0.0076	0.3537	0.0008	0.0866	-0.7483	0.0000	0.3737	0.0870	0.0066	-0.0080	0.0527	0.0125
Shanghai	-0.0087	0.3125	-0.0002	-0.0006	0.4116	0.0001	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0002
Jiangsu	-0.0049	0.2385	-0.0012	-0.0018	0.2639	0.0005	0.0436	-0.5911	0.0363	0.7145	0.1013	0.0076	-0.0023	0.0536	0.0085
Zhejiang	-0.0059	0.2763	-0.0101	-0.0009	0.3219	0.0044	0.0771	-0.5308	0.0534	0.7214	0.0548	0.0775	-0.0024	0.0462	0.0274
Anhui	-0.0086	0.2539	-0.0030	-0.0018	0.2835	0.0012	0.0550	-0.6194	0.0000	0.6807	0.0713	0.0021	-0.0022	0.0735	0.0188
Fujian	-0.0048	0.2512	-0.0086	-0.0004	0.2903	0.0056	0.0528	-0.6558	0.0625	0.6368	0.0586	0.0819	-0.0053	0.0496	0.0567
Jiangxi	-0.0054	0.3269	-0.0048	-0.0009	0.3295	0.0028	0.0737	-0.7420	0.0000	0.4738	0.0613	0.0154	-0.0052	0.0528	0.0480
Shandong	-0.0033	0.2037	-0.0006	-0.0016	0.2152	0.0002	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0008
Henan	-0.0059	0.2603	-0.0016	-0.0026	0.2727	0.0009	0.0308	-0.7259	0.0074	0.5679	0.0858	0.0003	-0.0087	0.0561	0.0140
Hubei	-0.0026	0.2762	-0.0844	-0.0009	0.3415	0.0427	0.0327	-0.8599	0.0025	0.2276	0.0744	-0.0079	-0.0154	0.0266	0.0417
Hunan	-0.0047	0.2811	-0.0153	-0.0008	0.3229	0.0114	0.0356	-0.8409	0.0000	0.3213	0.0640	0.0059	-0.0225	0.0346	0.0504
Guangdong	-0.0079	0.2647	-0.0175	-0.0009	0.3673	0.0090	0.0962	-0.4375	0.1144	0.7456	0.1322	0.0860	-0.0061	0.0402	0.0312
Guangxi	-0.0041	0.3054	-0.0184	-0.0007	0.3262	0.0113	0.0549	-0.8021	0.0000	0.3906	0.0185	0.0199	-0.0066	0.0400	0.0729
Hainan	-0.0057	0.3400	-0.0037	-0.0009	0.3211	0.0016	0.1034	-0.5545	0.0102	0.0233	0.6775	0.0589	0.0010	0.0637	0.0501
Chongqing	-0.0041	0.3353	-0.0214	-0.0008	0.3417	0.0113	0.0769	-0.7404	0.0000	0.1828	0.4272	0.0029	-0.0111	0.0326	0.0498
Sichuan	-0.0016	0.2987	-0.0614	-0.0011	0.3277	0.0508	0.0546	-0.7532	0.0015	0.1310	0.4577	-0.0066	-0.0094	0.0227	0.0520
Guizhou	-0.0035	0.1826	-0.0146	-0.0008	0.1788	0.0096	0.0089	-0.7958	0.0000	0.5483	0.0131	0.0001	-0.0105	0.0645	0.0406
Yunnan	-0.0012	0.2675	-0.0808	-0.0007	0.2899	0.0362	0.0336	-0.8506	0.0000	0.3322	0.0178	0.0003	-0.0360	0.0368	0.0586
Shaanxi	-0.0077	0.2810	-0.0046	-0.0025	0.3048	0.0020	0.0362	-0.8044	0.0017	0.4000	0.1391	0.0000	-0.0179	0.0498	0.0159
Gansu	-0.0124	0.3162	-0.0226	-0.0023	0.3481	0.0124	0.0939	-0.6195	0.0000	0.6083	0.1227	0.0038	-0.0167	0.0567	0.0583
Qinghai	0.0061	0.2602	-0.1443	-0.0020	0.2730	0.0818	0.0605	-0.6988	0.0109	0.1352	0.5648	0.0001	-0.0277	0.0265	0.1131
Ningxia	-0.0147	0.2548	-0.0015	-0.0049	0.2718	0.0006	0.0776	-0.5432	0.0026	0.7414	0.0999	0.0039	-0.0139	0.0730	0.0081
Xinjiang	-0.0054	0.2212	-0.0062	-0.0013	0.2355	0.0028	0.0241	-0.7691	0.0017	0.4881	0.2548	-0.0001	-0.0172	0.0505	0.0170

Table 4.18: Efficiency-improving Afforestation-based Reforms under LVES-1

Region	k_Y	k_C	k_R	l_Y	l_C	l_R	e_T	x_{TC}	x_{TG}	x_{NC}	x_{NG}	x_O	a	γ^*	β_5
Non-decreasing Reforms															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5643	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0029	0.0296	0.0000
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	0.0000	0.0548	0.0000
Hebei	-0.0041	0.1909	0.0031	-0.0014	0.2195	0.0183	-0.0141	-0.8690	0.0000	0.3983	0.0324	-0.0037	0.0000	0.0416	0.0015
Shanxi	-0.0048	0.1369	0.0065	-0.0014	0.1712	0.0221	-0.0258	-0.8473	0.0031	0.4822	0.0159	-0.0002	0.0000	0.0591	0.0022
Inner Mongolia	-0.0069	0.1569	0.0063	-0.0034	0.1767	0.0154	-0.0003	-0.6651	0.0017	0.7077	0.0254	-0.0014	0.0000	0.0835	0.0068
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5155	0.1141	0.0111	0.0000	0.0491	0.0012
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	0.0000	0.0506	0.0001
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	0.0000	0.0528	0.0008
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	0.0000	0.0536	0.0002
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	0.0000	0.0466	0.0002
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	0.0000	0.0736	0.0003
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	0.0000	0.0508	0.0005
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4655	0.0602	0.0151	0.0000	0.0537	0.0005
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	0.0000	0.0400	0.0007
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	0.0000	0.0562	0.0010
Hubei	-0.0068	0.2633	0.0558	-0.0019	0.3256	0.3107	0.0312	-0.8197	0.0023	0.2170	0.0709	-0.0075	0.0000	0.0279	0.0008
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3115	0.2228	0.0344	-0.8111	0.0000	0.3102	0.0618	0.0057	0.0000	0.0358	0.0016
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	0.0000	0.0407	0.0005
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3677	0.0174	0.0187	0.0000	0.0425	0.0005
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0010	0.0649	0.0000
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1742	0.4070	0.0028	0.0000	0.0342	0.0007
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3028	0.3417	0.0504	-0.6959	0.0014	0.1211	0.4229	-0.0061	0.0000	0.0246	0.0004
Guizhou	-0.0046	0.1812	0.0534	-0.0013	0.1775	0.1130	0.0088	-0.7897	0.0000	0.5442	0.0130	0.0001	0.0000	0.0650	0.0014
Yunnan	-0.0063	0.2537	0.0532	-0.0018	0.2751	0.3242	0.0319	-0.8068	0.0000	0.3159	0.0169	0.0003	0.0000	0.0388	0.0026
Shaanxi	-0.0077	0.2803	0.0245	-0.0026	0.3040	0.0696	0.0361	-0.8023	0.0017	0.3991	0.1387	0.0000	0.0000	0.0499	0.0018
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3405	0.1960	0.0918	-0.6057	0.0000	0.5950	0.1200	0.0037	0.0000	0.0579	0.0019
Qinghai	-0.0173	0.1964	0.2128	-0.0131	0.2064	0.6317	0.0457	-0.5281	0.0082	0.1027	0.4271	0.0001	0.0000	0.0350	0.0015
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2717	0.0289	0.0776	-0.5430	0.0026	0.7412	0.0998	0.0039	0.0000	0.0730	0.0020
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7669	0.0017	0.4868	0.2541	-0.0001	0.0000	0.0507	0.0017
Non-increasing Reforms															
Beijing	-0.0119	0.2920	0.0226	-0.0005	0.5644	0.1992	0.1442	-0.2604	0.0052	-0.2216	0.6442	0.0568	0.0000	0.0296	0.0002
Tianjin	-0.0081	0.3907	0.0003	-0.0019	0.4128	0.0017	0.1246	-0.5739	0.0048	0.5190	0.2345	0.0877	-0.0003	0.0548	0.0000
Hebei	-0.0041	0.1908	0.0030	-0.0014	0.2194	0.0183	-0.0141	-0.8689	0.0000	0.3982	0.0324	-0.0037	-0.0182	0.0416	0.0000
Shanxi	-0.0048	0.1368	0.0065	-0.0014	0.1712	0.0220	-0.0258	-0.8472	0.0031	0.4821	0.0159	-0.0002	-0.0184	0.0591	0.0000
Inner Mongolia	-0.0069	0.1568	0.0063	-0.0034	0.1765	0.0154	-0.0003	-0.6648	0.0017	0.7069	0.0253	-0.0014	-0.0404	0.0836	0.0000
Liaoning	-0.0049	0.2413	0.0198	-0.0014	0.2649	0.0537	0.0226	-0.7674	0.0018	0.5154	0.1141	0.0111	-0.0121	0.0491	0.0000
Jilin	-0.0046	0.3089	0.0499	-0.0022	0.2934	0.1162	0.0504	-0.8048	0.0004	0.3820	0.0785	0.0052	-0.0014	0.0506	0.0000
Heilongjiang	-0.0099	0.3994	0.0215	-0.0076	0.3531	0.0522	0.0865	-0.7471	0.0000	0.3731	0.0868	0.0066	-0.0080	0.0528	0.0000
Shanghai	-0.0087	0.3125	0.0002	-0.0006	0.4116	0.0015	0.1093	-0.4926	0.1075	0.5066	0.2185	0.4029	-0.0001	0.0403	0.0000
Jiangsu	-0.0049	0.2383	0.0131	-0.0018	0.2638	0.0339	0.0436	-0.5907	0.0363	0.7140	0.1012	0.0076	-0.0023	0.0536	0.0000
Zhejiang	-0.0061	0.2740	0.0411	-0.0010	0.3193	0.1210	0.0765	-0.5264	0.0530	0.7155	0.0544	0.0768	-0.0024	0.0466	0.0000
Anhui	-0.0087	0.2534	0.0197	-0.0018	0.2830	0.0568	0.0549	-0.6182	0.0000	0.6795	0.0712	0.0021	-0.0022	0.0736	0.0000
Fujian	-0.0057	0.2451	0.1117	-0.0008	0.2833	0.1885	0.0516	-0.6399	0.0609	0.6214	0.0572	0.0799	-0.0052	0.0508	0.0000
Jiangxi	-0.0057	0.3212	0.0901	-0.0011	0.3236	0.1641	0.0724	-0.7289	0.0000	0.4654	0.0602	0.0151	-0.0051	0.0537	0.0000
Shandong	-0.0033	0.2037	0.0009	-0.0016	0.2152	0.0056	-0.0090	-0.8232	0.0013	0.4481	0.0350	-0.1799	-0.0087	0.0400	0.0000
Henan	-0.0059	0.2599	0.0244	-0.0027	0.2724	0.0464	0.0308	-0.7249	0.0074	0.5671	0.0857	0.0003	-0.0087	0.0562	0.0000
Hubei	-0.0068	0.2632	0.0558	-0.0019	0.3255	0.3106	0.0312	-0.8196	0.0023	0.2169	0.0709	-0.0075	-0.0147	0.0279	0.0000
Hunan	-0.0065	0.2711	0.1436	-0.0017	0.3114	0.2228	0.0343	-0.8110	0.0000	0.3099	0.0618	0.0057	-0.0217	0.0358	0.0000
Guangdong	-0.0085	0.2614	0.0537	-0.0010	0.3628	0.1473	0.0950	-0.4322	0.1130	0.7365	0.1306	0.0850	-0.0061	0.0407	0.0000
Guangxi	-0.0064	0.2874	0.1598	-0.0020	0.3070	0.2985	0.0517	-0.7549	0.0000	0.3676	0.0174	0.0187	-0.0062	0.0425	0.0000
Hainan	-0.0059	0.3336	0.0748	-0.0010	0.3151	0.1777	0.1015	-0.5441	0.0100	0.0229	0.6648	0.0578	0.0000	0.0649	0.0001
Chongqing	-0.0054	0.3194	0.1212	-0.0014	0.3255	0.2801	0.0732	-0.7053	0.0000	0.1741	0.4070	0.0028	-0.0106	0.0342	0.0000
Sichuan	-0.0092	0.2759	0.1869	-0.0036	0.3027	0.3417	0.0504	-0.6959	0.0014	0.1210	0.4229	-0.0061	-0.0086	0.0246	0.0000
Guizhou	-0.0046	0.1812	0.0533	-0.0013	0.1774	0.1130	0.0088	-0.7897	0.0000	0.5441	0.0130	0.0001	-0.0105	0.0650	0.0000
Yunnan	-0.0063	0.2535	0.0532	-0.0018	0.2749	0.3240	0.0319	-0.8066	0.0000	0.3150	0.0168	0.0003	-0.0341	0.0388	0.0000
Shaanxi	-0.0077	0.2802	0.0245	-0.0026	0.3039	0.0696	0.0361	-0.8023	0.0017	0.3989	0.1387	0.0000	-0.0178	0.0499	0.0000
Gansu	-0.0141	0.3091	0.0787	-0.0029	0.3404	0.1960	0.0918	-0.6057	0.0000	0.5948	0.1199	0.0037	-0.0163	0.0579	0.0000
Qinghai	-0.0173	0.1964	0.2127	-0.0131	0.2064	0.6316	0.0457	-0.5282	0.0082	0.1022	0.4269	0.0001	-0.0209	0.0350	0.0000
Ningxia	-0.0147	0.2547	0.0099	-0.0049	0.2716	0.0289	0.0776	-0.5430	0.0026	0.7411	0.0998	0.0039	-0.0139	0.0730	0.0000
Xinjiang	-0.0055	0.2205	0.0256	-0.0013	0.2348	0.0730	0.0241	-0.7668	0.0017	0.4866	0.2540	-0.0001	-0.0172	0.0507	0.0000

Chapter 5

Regional Profile of Energy, Forests, and Province-level Environmental Policies: The Case of China

5.1 Introduction

This chapter can be regarded as an extension of Chapter 4. In Chapter 4 we employed China's province-level data at status-quo to investigate the existence of allocative efficiency-improving reforms in China's regional production. It is worth noting that such allocative inefficiencies are rampant across all 30 provinces in China. This is confirmed by four different production function specifications for intended output production. Our estimated optimal reforms for each province lead to efficiency improvements in the form of increasing final consumption without increasing the emission levels. Constrained by resource feasibility, our optimal policy reforms aim to reallocate the current inputs level to achieve improvements in efficiency. Hence, it seems necessary to review each province's specific situation, especially for current levels of input use and environment-related regulations to understand to what extent our optimal policy reforms as well as other types of reforms based on thermal energy, renewable energy, and afforestation proposed in Chapters 3 and 4 actually reflect the reality.

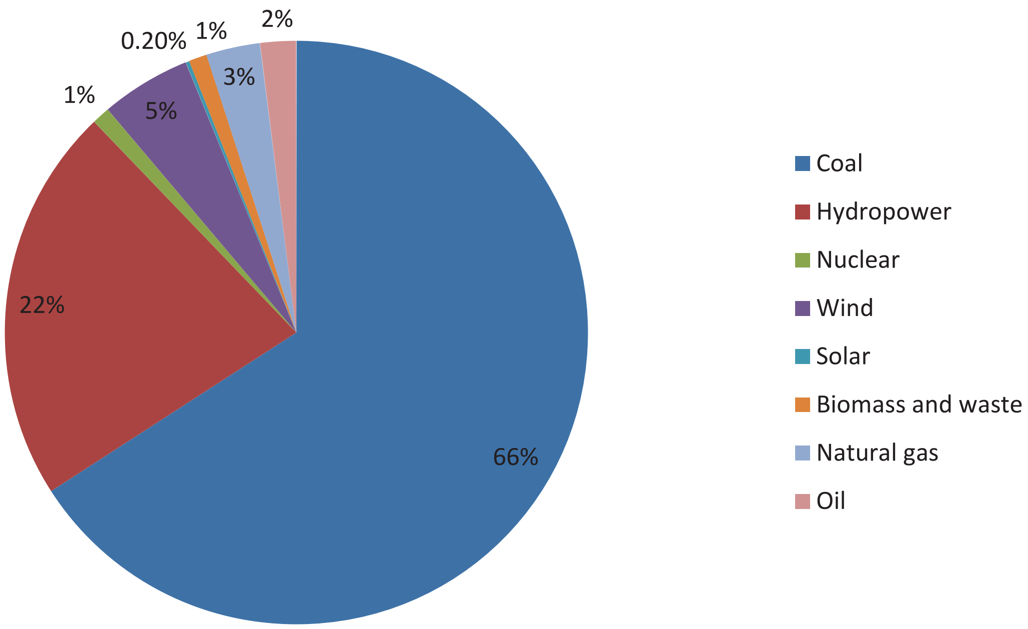
In this chapter we will explore more deeply into China's reality with respect to natural resources utilisation, especially for the energy and forestry sectors, and briefly study the carbon emission trading scheme that is currently being implemented in China. We would also like to provide a brief report on each province based on its own special geographical features and energy reserves to see to what extent the policy recommendations coming out of our analyses in Chapters 3 and 4 can help achieve not only the theoretical objectives of efficiency improvements under feasibility constraints of the economic model, but also truly meet each region's development requirements.

5.2 Overview of Energy and Forest Resources of China and Province-level Environmental Policies

5.2.1 Electricity

Fossil Fuel Thermal Power

China has become the largest power generator since 2011 (U.S. EIA, 2015). Specifically, thermal power is the predominant generating electricity in China, which has accounted for more than 70% of the total electricity generation since 2010 (IEA, 2014). By the end of 2012, more than 90% of thermal generating capacity was from coal-fired plants, which accounted for 66% of total installed electricity capacity. But the combined share of gas and oil is still less than 10% (see Figure 5.1).



Total installed capacity: 1,145 GW
Source: US IEA

Figure 5.1: China's Installed Electricity Capacity by Fuels in 2012

From the regional perspective, Jiangsu was the largest thermal power generation province in 2012, with total 394.3 billion kWh. Followed by Shandong and Inner Mongolia, with 324.1 and 302.9 billion kWh, respectively. Moreover, Guangdong, Henan, Shanxi, Zhejiang and Heibei were also high generation provinces, with more than 200 billion kWh (see Table 5.4). The two main reasons could be that firstly, the high thermal power generation could be able to meet the high energy demand of economic development, like Guangdong, Jiangsu, Shandong and Zhejiang. These four provinces are obviously the top four electricity consumers shown in Table 5.4, because of their higher levels of economic development. Based on the figures released by the National Bureau of Statistics of China (NBSC), Guangdong produced the highest GDP in 2012, with 5,706,792 million RMB, followed by Jiangsu, Shangdong and Zhejiang. Due to the highly increasing demand of the energy in development process, Guangdong also became the largest electricity net importer, even if it was one of the high thermal power generators in 2012 (see Table 5.4). Similarly, the other three high developed provinces are all electricity net importers. Secondly, some high thermal power generators, like Inner Mongolia and Shanxi, are both main coal mines in China.[1] Due to the abundance of coal resources in these regions, the thermal power production has become an industry whit a high comparative advantage. Moreover, in these regions, the high level of thermal power generation exceeds their own demand, which makes Inner mongolia and Shanxi the two largest electricity exporters in China.

Furthermore, according to the IEA report in 2010, 49.28% of Chinas carbon emissions were from thermal power production (Wang, Xie, Shang and Li, 2013). Therefore, the environmental policies related to carbon reduction in thermal power plants should be taken into consideration in the future thermal power industry development, especially for larger thermal power producers. Meanwhile, the development on new clean power generation combined with their own regional advantages might be the other effective method to meet the energy demand and avoid further deterioration of the environment, such as the nuclear power development in Guangdong, Jiangsu and Zhejiang, and wind power application in Inner Mongolia and Gansu.

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[1] More details are discussed in primary energy part

Hydropower

China has rich water and river resources. Due to the strong policy drivers, the hydropower industry in China has developed rapidly since the 1980s. Based on China's national census in 2005, the gross theoretical hydropower potential was estimated as 694 GW (Huang and Yan, 2009). China led the world in total exploitable hydropower installed capacity with 213 GW at the end of 2010.[2]

Because of the vast terrain and diverse climates in China, the water resources show an extremely uneven geographical distribution. Southwest China has the most abundant hydropower resources. Based on the Table 5.1 and Figure 5.2, Sichuan had the largest hydropower generation with 154.5 billion kWh in 2012, followed by Hubei and Yunnan with 138 and 124 billion kWh, respectively. The total hydropower generation from these three provinces accounted for 48.78% of the country's generation. However, the total hydropower generation in five Eastcoast regions, Beijing, Tianjin, Shanghai, Jiangsu, and Shandong with their relatively high level of economic development, accounted for only 0.24% of the nation's total amount of generation in 2012.[3]

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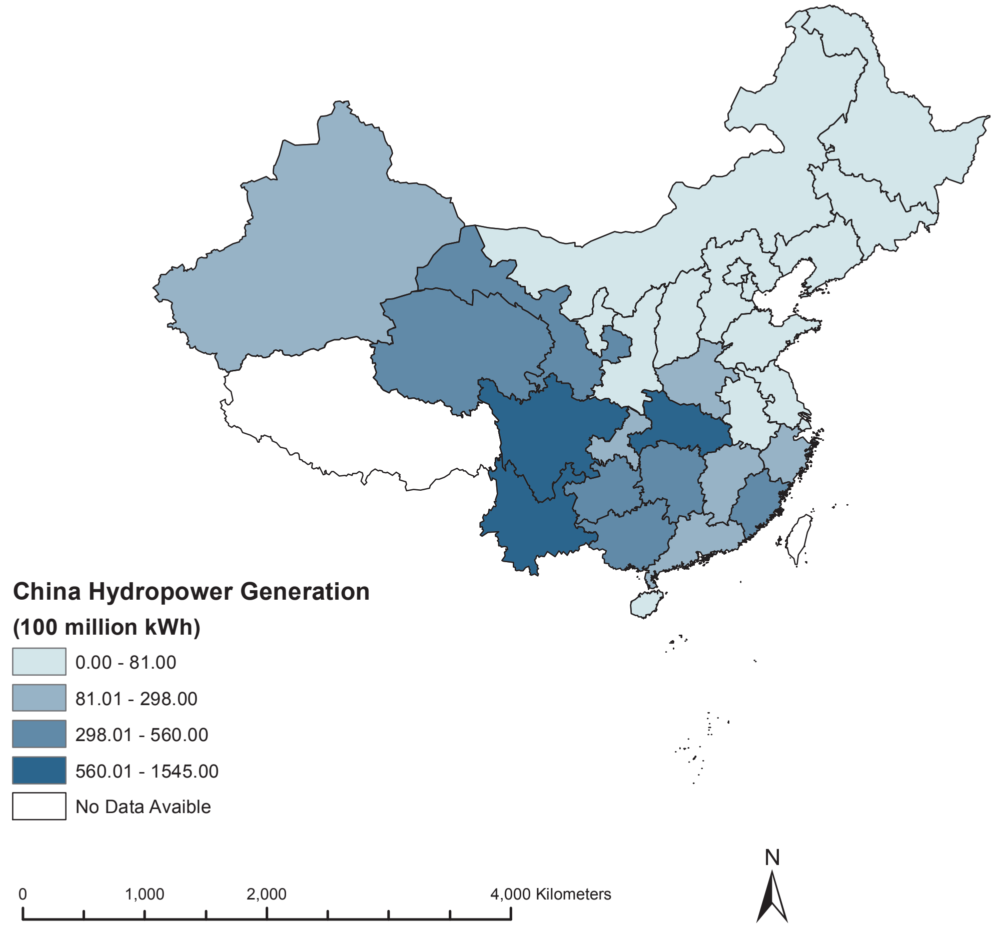
[2] Source: National Energy Administration, 2011.

[3] Source: Our own calculation in this study



Source: National Bureau of Statistics of China

Figure 5.2: Spatial Distribution of Hydropower Generation in China 2012

In order to solve the energy shortage in the east and enhance the utilisation of hydropower resource in west, the Chinese government proposed the “West-East Electricity Transfer Project” during the Tenth Five-Year Plan (2000-2005). This project might expand the capacity of electricity generation in western provinces through building up new thermal bases and hydropower stations, which may result in the development of infrastructure and energy sector in some western provinces. Moreover, the resulting increase in electricity exporting from western area could also bring energy security and support engine of economic growth to the east coast regions.

Table 5.1: Renewable Power Generation Information in 2012

Region	id	Hydropower gen*	Nuclear power gen*	Wind power gen*
Beijing	1	7	0	3.1
Tianjin	2	0	0	4.7
Hebei	3	10	0	126
Shanxi	4	44	0	36
Inner Mongolia	5	29	0	284
Liaoning	6	64	0	79
Jilin	7	79	0	44
Heilongjiang	8	18	0	51
Shanghai	9	0	0	6.3
Jiangsu	10	12	162	37
Zhejiang	11	220	346	7.8
Anhui	12	36	0	4.6
Fujian	13	476	0	28
Jiangxi	14	146	0	3.2
Shandong	15	1.2	0	63
Henan	16	128	0	3.3
Hubei	17	1380	0	2
Hunan	18	446	0	2.7
Guangdong	19	298	474	24
Guangxi	20	524	0	0.8
Hainan	21	24	0	4.7
Chongqing	22	210	0	0.8
Sichuan	23	1545	0	0.4
Guizhou	24	560	0	4.9
Yunnan	25	1240	0	28
Shaanxi	26	81	0	2.6
Gansu	27	344	0	94
Qinghai	28	458	0	0.2
Ningxia	29	19	0	33
Xinjiang	30	140	0	49

Source: China Electric Power Yearbook

* Unit of Hydropower, Nuclear and Wind gen (generation) is 100 million kWh

5.2.2 Primary Energy

Coal

China is currently the world's largest coal producer and consumer, accounting for about half the world's coal consumption since the early 1980s, which also let its becoming one of the leading energy-related carbon dioxide emission countries. According to the World Energy Council's report in 2011, China held an estimated 126 one billion short tons of recoverable coal reserves, the third largest in the world after the Unite States and Russia. This is equivalent to about 13% of the world total coal reserves (U.S. EIA, 2015). Although there are 28 provinces producing coal in China, the major coal resources and virtually all of the large state-own mines are relatively concentrated in a few provinces (regions), such as Shanxi, Inner Mongolia, Xinjiang, and Shaanxi (see Table 5.2). In 2012, reserves of coal resources in this four provinces accounted for 69.74% of total reserves.[4] Shanxi ranked the first with a share of 39.52% of the total, followed by Inner Mongolia with 17.47%. In addition, the current 12,000 coal mines in China mainly produce bituminous coal and an amount of anthracite, metallurgical coke and lignite (Xinhua News, 2013). Coal is mainly used for electricity and heat generation. Most of China's coal resources (for electricity and heating usage) are located in the north central and north western regions, while the higher valuation of coking coal and anthracite reserves are mostly found in the central and coastal parts of China.

Table 5.2: Spatial Distribution of Coal Resource Reserves in China 2012

Area	**Province(proportion%)**	**Reserves** (10^8 **tons**)	**Proportion**(%)
Eastcoast	Beijing (0.16), Tianjin (0.13), Hebei (1.72), Shanghai (0), Jiangsu (0.47),Zhejiang (0.02), Fujian (0.19), Shandong (3.47), Guangdong (0.01), Hainan (0.05)	143.05	6.22
Central	**Shanxi** (39.53), Anhui (3.51), Jiangxi (0.18), Henan (4.31), Hubei (0.14), Hunan (0.29)	1101.86	47.93
Northeast	Liaoning (1.39), Jilin (0.43), Helongjiang (2.68)	103.38	4.51
West	**Inner Mongolia** (17.47), Guangxi (0.09), Chongqing (0.86), Sichuan (0.23), Guizhou (3.02), Yunnan (2.57), **Shaanxi** (4.74), Gansu (1.48), Qinghai (0.69), Ningxia (1.41), **Xinjiang** (6.63)	950.45	41.35

Source: NBSC and author's calculation

China's coal industry can be classified as large state-owned coal mines, local state-owned coal mines, and thousands of township coal mines. The top of the state-owned coal companies, including Shenhua Group and China National Coal Group (China's largest coal company), produce around 50% of the total coal. Local state-owned enterprises produce about 20%, and small cities and towns coal mine production output accounts for 30% each year (U.S. EIA, 2015). It has been reported that there are about 10,000 small coal

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[4] Source from: China Statistical Yearbook 2013

mines in China, and most of them have insufficient investment, outdated equipment, and poor safety practices, and also are typical pollution sources. In order to promote better development of the coal industry, in recent years, the Chinese government has adopted a series of measures to regulate coal production, such as shutting down and implementing corrective measures for small-scale coal production, while encouraging eco-friendly technological innovations in large coal enterprises. By the end of 2014, China had reformed the tax structure of coal. The resource tax levied on coal mining shifted from a volume-based system into a value-based system, which indicates local governments are permitted to collect between 2% to 10% of the value of domestic coal sold. In addition, the central government also cancelled all surcharges and fees for coal production. This reform has reduced the production costs of coal producing companies.

Natural Gas

China's natural gas resources are unevenly distributed, and one distinctive characteristics is that the supply regions, which are located in the northeast and western areas, are far from the demand centers around the east coast area (Li, 2015). By the end of 2012, the five primary gas producing provinces were Sichuan (Sichuan Basin), Shaanxi (Ordos Basin), Xinjiang (Tarim and Junggar Basins), Qinghai (Qaidam Basins), and Heilongjiang (Songliao Basin) (see Figure 5.3).[5] On the other hand, China's inland gas fields are mostly small and medium size. Due to the complex geological structure of most gas fields, there are still some difficulties in conducting large-scale exploration and development.[6]

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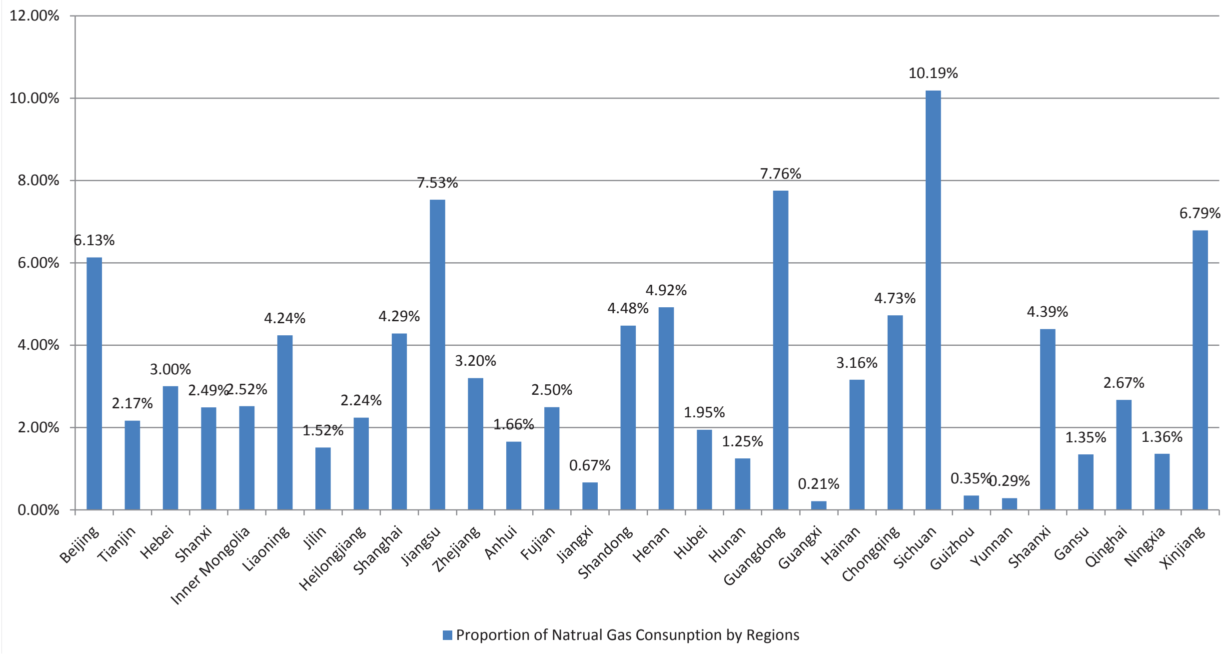
[5] In addition, China has some offshore natural gas fields located in the East China Sea and the South China Sea

[6] Based on the information released by the Energy Research Institute National Development and Reform Commission.`http://eng.eri.org.cn/`

Source: China National Petroleum Corporation (CNPC) and Higashi (2009)

Figure 5.3: China's Natural Gas Basins

From the demand side, China experienced a dramatic rising trend in the demand for gas during current years. U.S. EIA (2015) found that China's gas consumption in 2013 rose to 5.7 trillion cubic feet (Tcf), an increase of 12% compared to the figure in 2012. Moreover, China has already become a net natural gas importer since 2007. Above all, Sichuan was the largest gas consumer in 2012, accounting for 10.19% in total gas consumption in China. The second largest gas consumer was Guangdong, accounting for 7.76% of the total (see Figure 5.4). However, the consumption structures between these two leading consumers are quite different. In 2012, the household and industrial usage accounted for 42% and 36% in Sichuan's total gas consumption, while the power and heat generation usage only accounted for less than 1%. On the other hand, around 50% of natural gas was used for generating power and heat in Guangdong, and residential use was only about 11%. At the national consumption level, the power and heat consumption represented approximately 18% (Li, 2015). Specifically, most gas-fired power plants are located in the China's south east coastal areas. Li (2015) indicates, in coastal areas, gas has recently started to replace coal in power generation, one reason being that a number of new regional government policies have put some restrictions on the development of coal-fired plants due to environmental consideration. Hence, gas fired power generation and energy imports have become two feasible options for providing necessary electricity in regions with limited renewable energy sources such as wind or solar power.



Source: NBSC

Figure 5.4: Proportion of Natural Gas Consumption by Regions in 2012

Oil

Due to the rapid demand growth in oil products, China has surpassed the United States to become the largest global net importer of oil since 2014, and China's oil import dependence reached 60% in 2014.[7] In order to meet the oil demand in economic development, China has also experienced a moderate increase in domestic oil production. According to an IEA report, China's oil output has been boosted by more than 7% since 2010. Based on the related statistics, the capacity of China's crude oil production is mostly located onshore, and accounts for approximately 80% of the total production. The remaining 20%

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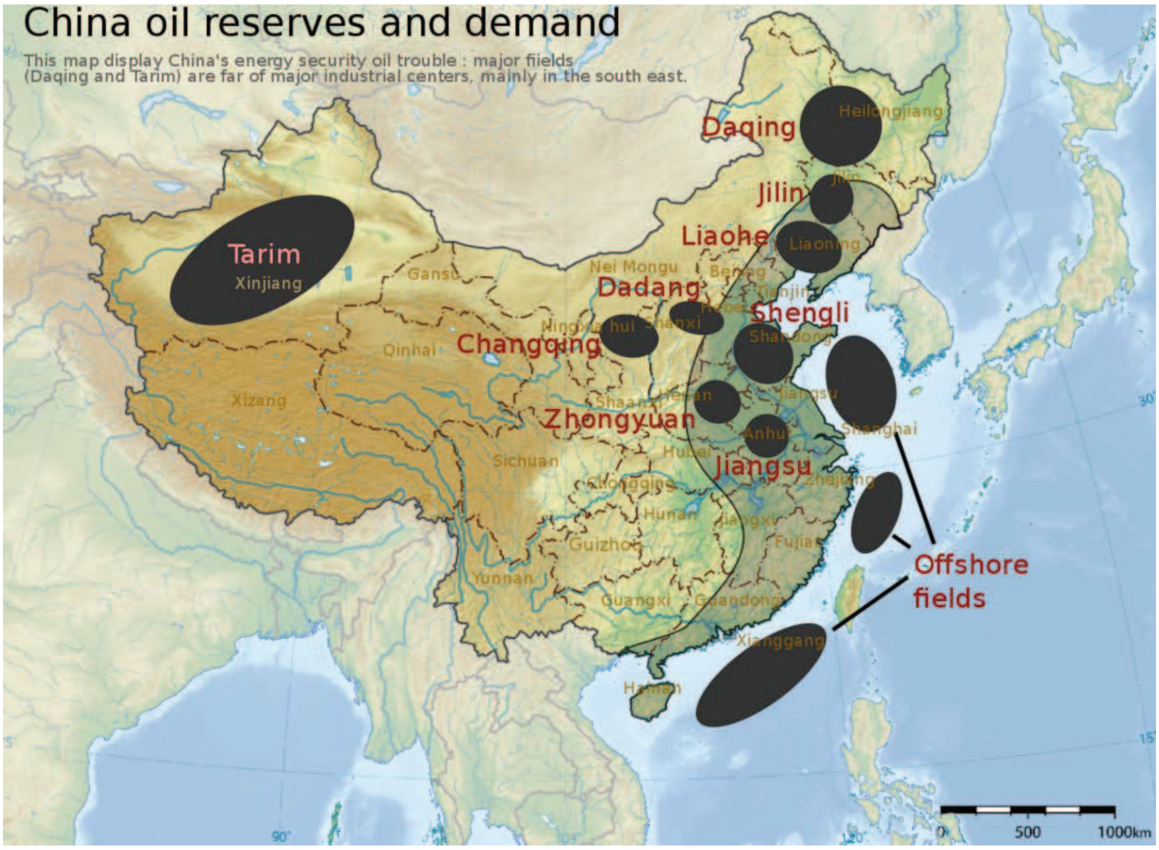
[7] The number comes from report of The National Bureau of Asian Research. http://nbr.org/downloads/pdfs/eta/Weidong_interview_072414.pdf

of crude oil output is from shallow offshore sources.[8] Specifically, the main oil fields are located in the northeast and north central regions (see Figure 5.5). However, U.S. EIA (2015) found some of larger China's onshore oil fields were mature and showed the declining production in recent years, due to the heavily exploitation since the 1960s.



Source: IEA (2000)

Figure 5.5: China's Oil Reserves and Fields

From Figure 5.6, we can observe China's fuel oil consumption structure. Industry and transport are the main sectors of oil demand, which takes more than 98% of total oil consumption. More specifically, industry oil consumption accounts for 60.86% and transport consumption is 37.57%. According to Table 5.4, Shandong, Shanghai, Guangdong, Liaoning and Zhejiang were the top five fuel oil consumers in 2012. The diverse consumption structures for these regions can be observed in Figure 5.7.[9] Shandong consumed the highest level of fuel oil and the majority came from the petroleum refineries inputs. Sim-

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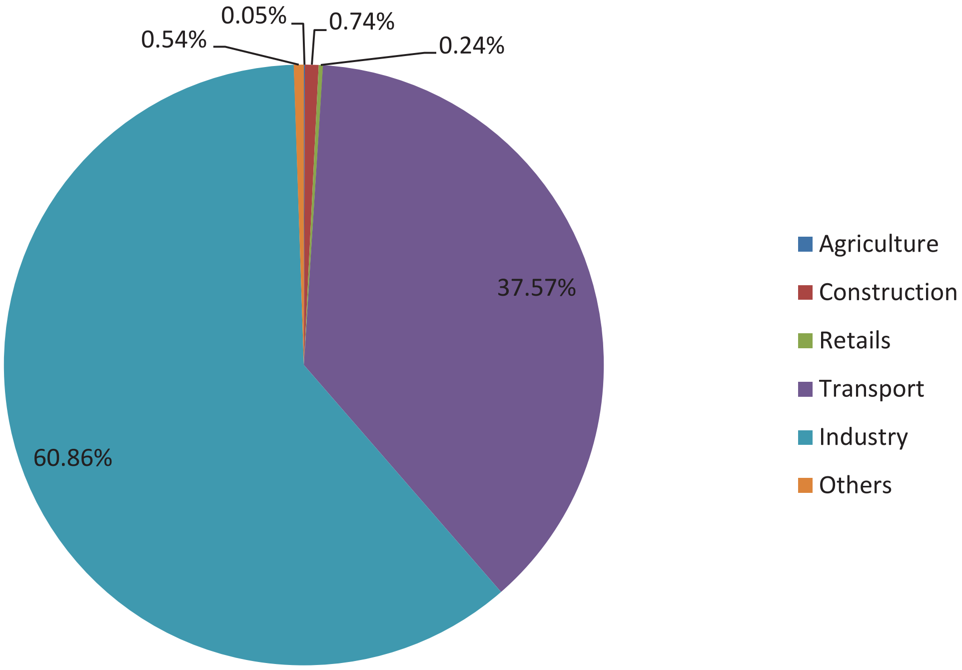
[8] IEA estimates the percentage by using data from Facts Global Energy (FGE), source from: China Oil and Gas Monthly Data Tables, March 2015.

[9] Other fuel oil use categories in Figure 5.7 include industry non-energy use, construction use, retail and residential use etc., which accounts for a small proportion.

ilarly, Zhejiang's largest consumption also came from petroleum refineries. By contrast, Shanghai and Guangdong, the second and third largest consumers, had no fuel oil input from the petroleum refinery industry. Moreover, the largest oil consumption for Shanghai was transport sector. Due to the rapidly increasing trend in passenger traffic and rotation volume, freight transport and cargo rotation volume from 2000 to 2011, the energy used in transport, especially petroleum products consumption, has continued to grow at a significant rate (Song et al., 2014). The other finding shown in the consumption structure table is that industry use accounts for a certain proportion for all regions rather than the agriculture use. In addition, Guangdong also consumed more fuel oil for the heating supply.

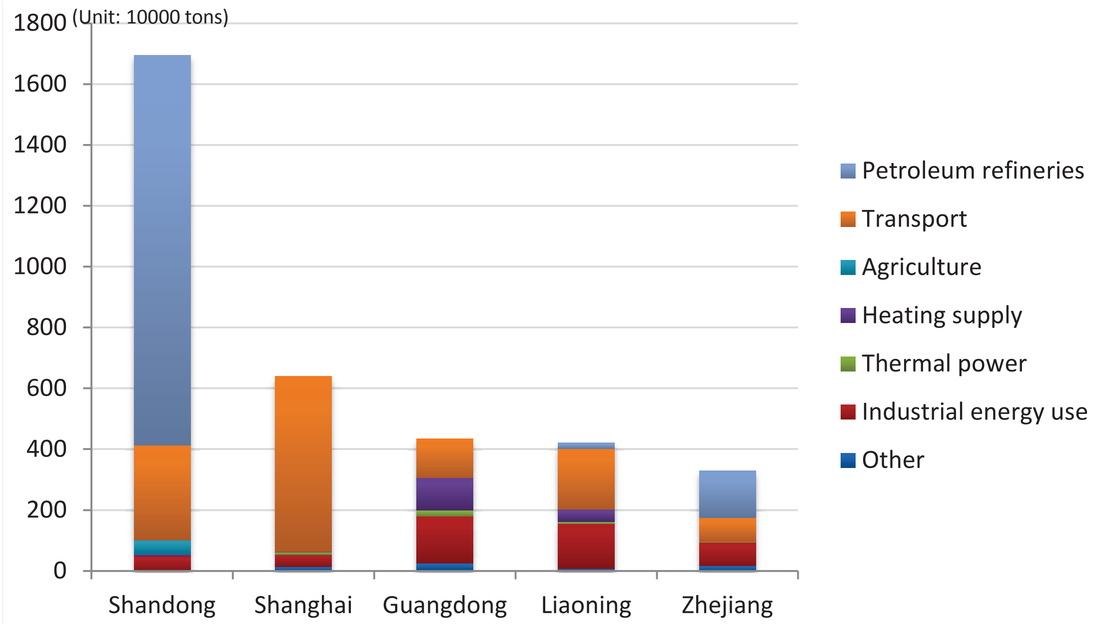


Total fuel oil consumption: 36.83 million tons
Source: NBSC and our own calculation

Figure 5.6: China's Oil Fuel Consumption Structure in 2012

5.2.3 Forest

Forestry plays an important role in helping China to implement its sustainable development strategy, which is especially important to China's western development programme. Since forests have a huge capacity for carbon storage, afforestation seems an effective method currently to counteract growing carbon emissions and thereby to mitigate the in-

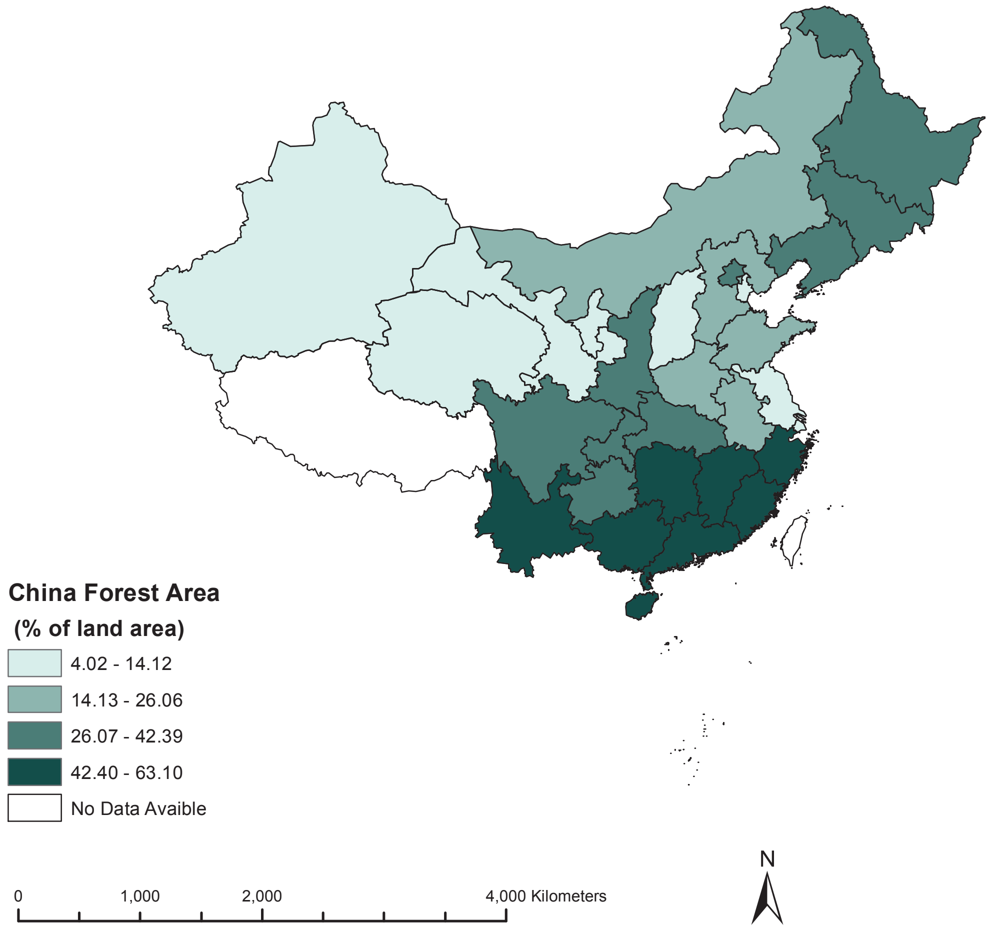


Source: China Energy Statistical Yearbook

Figure 5.7: Regional Oil Fuel Consumption Structure of Five Main Provincial Administrations in 2012

fluences from global climate change.

In China, the total forest area was recorded at 195.5 million hectares, including 119.7 million hectares of natural forest. According to the Seventh National Forestry Resources Inventory (from 2004 to 2008), the overall forest area increased by 20.5 million hectares after the Sixth National Forestry Resources Inventory (from 1994 to 1998). Therefore, China has become the fifth largest forest area in the world, with increasing afforestation areas in recent years. However, in relation to China's population, the per capita forest area is only one quarter of the world's average. What is more, the percentage of forest cover in China is only two thirds of the world's average. In addition, the forests are unevenly distributed (see Figure 5.8). The highest percentage forest cover (% of land area) ranges from 42.40% to 63.10% in some southern provinces, including Guangdong, Hainan, and Yunan etc., and the lowest coverage (from 4.02% to 14.12%) comes from some provinces in western areas, such as Xinjiang, Qinghai, and Gansu. Such significant uneven distribution is mainly due to the different rainfall levels and weather conditions across the country, but it also seems important for the Chinese government to further improve the management of the country's plantations, especially for the lower forest covered regions, and to enhance the environmental contribution of the forests in these regions as important eco-systems.



Source: National Bureau of Statistics of China

Figure 5.8: Spatial Distribution of Forest Coverage in China 2012

5.2.4 Emission Trading Scheme

In order to promote the market based approaches in the application of environmental policy instruments, China's State Council has announced a plan to establish a carbon emissions trading scheme and list this plan as an important part of national energy and climate policy making in the twelfth Five-year Plan (from 2011 to 2015) (Zhang et al., 2014). Following this decision, China's National Development and Reform Commission selected five cities and two provinces, including Bejing, Tianjin, Shanghai, Chongqing, Shenzhen, Hubei and Guangdong, as pilots to implement and develop emission trading plans from 2013 to 2014 and extend the experience to the whole nation from 2016 to 2020.[10] The location of the pilots shows in Figure 5.9.

Figure 5.9: Approved Pilots of Carbon Trading Schemes in China

More details are shown in Table 5.3. Emission caps and allowance structures are largely different among these pilots, due to various economic development levels and locations. The highest level of cap is in Guangdong, which does not include Shenzhen city. Specifically, Shenzhen has the largest number of covered entities in spite of the lowest number of emission caps. One reason may be the significant difference in their industrial structures as Shenzhen's main industry sectors are tertiary and service industries while Guangdong concentrates on heavy industry, which probably generates more carbon emissions (Xiong et al., 2015). The design of China's carbon emission trading system has also taken actual individual needs and local industrialization levels into consideration. Regarding the aspect of allowance allocation, Beijing, Shenzhen, Hubei, and Guangdong will separate the quota of allowances into existing facilities, and production expansion, while, Shanghai and Tianjin will consider the existing facilities and new projects. However, Chongqing

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[10] The pilots are all provincial administrative regions, except Shenzhen. Shenzhen is a major city in Guangdong province but currently holds sub-provincial administrative status.

can only allocate all allowances to existing facilities.

Table 5.3: Key Features of China's Carbon Emission Trading Pilots

Pilot	Start year	Emission cap*	Covered entities	Allowance price**
Beijing	2013	50	490	9.28
Tianjin	2013	160	197	3.79
Shanghai	2013	160	200	7.68
Chongqing	2014	125	242	4.92
Shenzhen	2013	33	635	8.96
Hubei	2014	324	138	3.76
Guangdong	2013	408	211	9.31

* Unit of emission cap is million metric tons.
** Unit of allowance price is USD/ton, the price is updated to 30 July 2014.
Souce: Munnings et al. (2014)

Currently, China's carbon emission trading system mainly uses a free distribution approach to allocate allowances to covered entities in the initial stage. The competitive auction and fixed price sales are taken as supplementary measures for Beijing, Hubei and Shenzhen. Some dynamic management mechanisms are also used as adjustments. For example, in Hubei, if an entity's actual emission is over or less than 20% compared to the allocated allowance, the local government has the right to add or take back a certain amount of pre-allocated allowance. Similarly, Chongqing also applies this ex-post adjustment, and has specified the up and down range as being 8%.

Lastly, there are some concerns related to China's carbon emission trading system. Xiong et al. (2015) point out that the current allowance allocation mechanism may result in an over-supply of allowances, a heavy reliance on historical emission data may lead to an unrealistic emission cap estimation, and also there are clarity and transparency issues related to the trading market. Hence, these concerns require the Chinese government to continue to improve the feasibility of the carbon emission trading scheme and carefully identify solutions to address these issues in the future.

5.2.5 Province Report

Beijing

Beijing is the cultural and political center of China, and also one of the most developed and prosperous regions in China. Its economy is based on the high-end manufacturing and service sectors. To support the high speed economic development, its energy consumption is very high and the majority of electrical energy is still imported (see Table 5.4). On the other hand, Beijing also has many energy use restrictions with growing concerns about Beijing's environmental quality in recent years. Especially in 2008, coal consumption was restricted by companies and households, and several heavy polluting industrial facilities (e.g. oil refineries and steel making factories) were expected to move out of city and the numerous coal-fired thermal energy plants were required to reduce their emissions by 30% before June 2008 (Liu et al., 2012). According to the future municipal economic plan, the government will ban the new coal-fired thermal power plants after their existing ones are expected to be replaced by gas-fired plants by 2017.[11]

As the capital of China, Beijing's air pollution issue has become an important economic and social concern in China. Hence, in recent years, the government in Beijing is taking action that will bring emissions under control. For example, the government announced that they would make efforts to raise the share of gas in total energy consumption from 14% to 35% over the period from 2012 to 2017, and to drop the share of coal use from 24% to 10%.[12] In addition, Beijing has implemented the carbon emission trading scheme since 2013. These efforts are trying to control air pollution by adjusting the energy structure, but the key question is whether the shift from coal to renewables and natural gas can be achieved.

Apart from air pollution, Beijing suffered from a water shortage for a long time. The per capita water resource was only 300 cubic meters in 2007. It was 1/8 of Chinas average

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[11] See, "Coal-fired plants in Beijing on way out with new ban." China Daily. Updated: 26th May 2015. http://usa.chinadaily.com.cn/china/2015-05/26/content_20818662.htm

[12] Source: Beijing Clean Air Action Plan (20132017) [in Chinese] (Beijing Municipal Government, 2013); www.beijing.gov.cn

level and was far below the world's average level, and even was lower than the severe standards of 1,000 cubic meters per person (Zhang et al., 2007). This fact will greatly affect the hydro power utilization in Beijing. However, Beijing's forest resource potential is rather high. In 2012, the forest coverage of Beijing reached 31.72%.

Tianjin

Tianjin is located in the east of Beijing and along the Bohai Gulf, surrounded on most sides by Heibei province. In 2009, the manufacturing sector became the largest (54.8%) and fastest-growing (18.2%) sector of Tianjin's economy. Following exploration significant petroleum and natural gas reserves have been found underground in the plains and in the continental framework of the Bohai Sea. Hence, as a costal municipality the facing Bohai Sea, Tianjin has about 1 billion tons of petroleum deposits, which contain some important oilfields (Guo et al. (2015), p.147.) From Table 5.4, we can also see that the oil consumption in Tianjin accounts for a relatively large proportion of total energy consumption. But in terms of electrical energy use, Tianjin also needs to rely on a certain percentage of imports.

Similar to Beijing, air quality has emerged as a major concern in Tianjin. In 2014, Tianjin enacted new laws in an attempt to lower the city's pollution levels. These measures included several restrictions on days of severe pollution; halving the number of vehicles allowed on roads, halting construction and manufacturing activity, closing schools, and halting large-scale outdoor activities. Furthermore, Tianjin has also been the first pilot in the emission trading scheme trial since 2013, which may support Tianjin in establishing a more comprehensive system of environmental protection. However, due to its geographical condition, the current forest coverage is still quite low.

Hebei

Most parts of Hebei lie within the North China Plain with the hills and mountains located in its western part. In 2014, Hebei's GDP was 2.942 trillion RMB, ranked 6th in China. Its economy is largely dominated by steel manufacturing, iron and steel industries. Despite Hebei having a strong manufacturing base, over 40% of the population still work in agriculture, forestry and livestock sectors, with plenty of these crops able to feed Beijing and Tianjin.

Due to the high proportion of heavy industrial sectors in the economic structure, Hebei's total coal consumption was ranked 4th and carbon emissions was ranked 2nd in 2012 (see Table 5.4). In recent years, the air pollution problem in Hebei has become very serious. According to the information released by China's Ministry of Environmental Protection, there are seven cities in Hebei listed as the top ten severely polluted cities in China.[13] This alarming environmental situation is forcing the provincial government to take stern measures to curb air pollution. By 2017, the Hebei provincial government plans to relocate 123 heavy polluting companies, attempting to move the large iron and steel plants out of big cities. The government is also working to improve the energy efficiency of energy-intensive industries in the province. In 2011, the Asian Development Bank completed the disbursement of a 100 million USD loan to companies in Hebei for implementing energy efficiency projects, which aims to achieve the energy saving target of 7,799 TJ/year and green gas emission reduction target of 668,669 tCO_2/year in the following twenty years.[14]

Shanxi

Shanxi is a province of the northern part of China, belonging to the central economic region. In 2012, Shanxi's nominal GDP was 1.12 trillion RMB. Economically, Shanxi per capita GDP is lower than the national average, but Shanxi is China's important energy base with foundation reserve of coal resource accounting for 39.53% of China's total reserve (see Table 5.2). As a result, the province's economy is heavily dependent on coal mining. It is also home to the largest group of coal companies in China. Huge coal reserves also attract investment into the railways, power plants and metal refining and other energy related product research. However, Shanxi is very inefficient in energy and mining

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[13] See, "Air pollution in seven Hebei cities ranked among 10 worst." China Daily. Updated: 14 October 2015. `http://www.chinadaily.com.cn/china/2015-10/14/content_22187540.htm`

[14] Source from: 2011 Clean Energy Investments: Project Summaries, Clean Energy Investments Project Summaries, Asian Development Bank.

accident rates are very high (Wang et al., 2011). Although the local government hopes to strengthen the traditional industries, it wants to reduce its reliance on coal. Since 2008, many private coal mines have been closed or taken over by state-owned enterprises.[15]

In 2012, Shanxi produced 245.4 billion kWh of thermal electricity, and was one of the top five thermal producers among 30 provinces, but it only generated 4,400 million kWh of hydro electricity. The huge total amount of electricity generation made Shanxi a major net electrical energy exporter in China (see Table 5.4). In terms of forest resources, Shanxi's forest coverage accounts for 14.12% of its total area.

Inner Mongolia

Inner Mongolia is a province-level autonomous region, located in the north part of China, and belongs to the China's western economic region. As the third-largest land area of the province in China, Inner Mongolia is China's largest livestock producer. In recent years, the province's economic growth has recovered sharply because of the discovery of huge coal and other energy products resources. In 2012, Inner Mongolia's nominal GDP was 1.6 trillion RMB, and it was also the second largest thermal energy producer among 30 provinces with 302.9 billion kWh of electricity generated. In addition, Inner Mongolia was also the largest electrical energy exporter with around 132.5 billion kWh of electricity transported to other provinces in 2012. Abundant mineral resources are an important guarantee for the development of energy intensive industry in Inner Mongolia. According to a survey from the National Bureau of Statistics of China (NBSC), Inner Mongolia's proven coal reserves account for 17.47% of the total country's coal reserves (see Table 5.2). Similar to its fossil fuel resources, the Inner Mongolia is also abundant in renewable energy resources, especially for wind and solar power. In 2012, wind power generation reached 28.4 billion kWh, ranked the first among 30 provinces (see Table 5.1).

Inner Mongolia is China's important ecological security barrier, and also one of provinces which have the relatively abundant forest resources.[16] In 2012, the forest coverage was

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[15] See, "King coal's misrule", The Economist. Nov 28th 2015.

[16] Source:`http://www.nmg.gov.cn/quq/zykc/201506/t20150615_398120.html`

20% of the province's total area.

Liaoning

Liaoning is located in the northeast of China. It is possible to think of Liaoning as three approximate geographical regions: the highlands in the west, the plains in the middle, and hills in the east. Among the three provinces in northeast China, Liaoning has the largest economy in terms of GDP. In 2011, its nominal GDP was 2.2 trillion RMB, ranked 7th in China. The leading industries include machinery and equipment, petrochemicals, and metallurgy. Large-scale industrial production requires the consumption of a considerable amount of energy and natural resources. Rich deposits of crude oil resource have become one important guarantee for Liaoning's growing energy demand (Liaohe Oilfield. See, Figure 5.5).

To improve the energy consumption structure, Liaoning has invested significantly in building natural gas power plants and pipes in 2010. In Shenyang, the provincial capital, most small coal-fired boilers have been replaced by a heating system with electricity to reduce emissions, especially in new residential areas, and coal heating had been replaced by natural gas (Larson, 2011). According to Larson (2011), such replacement of coal by gas and relocating the heavy industry facilities in the outer suburbs have been made Liaoning significantly less polluting than heavy industry elsewhere in China. Furthermore, the Hongyanhe nuclear power plant construction was expected to be completed and start in operation in 2015, which has made Liaoning become another new province which can generate nuclear power expect for Zhejiang, Jiangsu and Guangdong.

Jilin

Jilin is one of three provinces in northeast China. In 2012, Jilin's nominal GDP grew over 12% and reached 1.19 trillion RMB, while agriculture still counts as one of the largest industries. The secondary and tertiary sectors have driven economic growth in recent years. Ongoing economic reform aims to improve the province's future development achievements, including modernizing traditional heavy industries and promoting the efficiency of state owned enterprises. In terms of energy utilisation, Jilin is abundant in reserves of oil shale, and the Songliao Basin (see Figure 5.3) is an important petroleum production base that also has shale gas and oil potential, which has been recognized in recent years. Although the gas-fired thermal maturity in Jilin is relatively low (Kuuskraa et al., 2013), the widespread use of natural gas in Jilin might be possible in the future.

Jilin is rich in water resources with the total water reserve being around 40.4 billion cubic meters. However, hydropower generation was still low in 2012 (see Figure 5.2). The hydropower plants concentrated in Jilin are mostly small scale (Liu, 2013), but with its excellent water resources and political intent for sustainable development, hydropower is expected to be further developed in Jilin. Meanwhile, Jilin is also an important forestry base in China, with live timber amounting to 0.84 billion cubic meters, ranking sixth in the country. The Changbai Mountains area is one of China's six major forestry areas.

Heilongjiang

Heilongjiang is one of the three northeast provinces in China. It borders Russia across the Heilongjiang and Wusuli rivers. Following the opening of the Daqing oilfield in 1959, Heilongjiang was one of the first regions in China to industrialise, and became a significant source of petroleum production and raw materials base in China. In 2012, Heilongjiang's nominal GDP was 1.37 trillion RMB. Since 1999, Daqing oil fields have been depleted and oil production dropped significantly (Hu et al., 2011; Höök et al., 2010). This situation could cause huge pressure on Heilongjiang's energy industries and also requires more efforts to search for and build up a new economic growth engine in the future.

The long-term ecological development in Heilongjiang has created favourable conditions and it has become a national ecological pilot province in China. In addition, Heilongjiang also has vast forest resources with 42.39% forest coverage, which has made Heilongjiang become one of the major terrestrial ecosystems in northeast Asia, and an ecological barrier in the northeast of China.

Shanghai

Shanghai is washed by the East China Sea in the east and Hangzhou Bay in the south. The Yangtze River pours into the East China Sea through the north part of city. It is located in the central position along China's east coastal line.[17] Shanghai is the commercial and financial centre of mainland China, as exemplified by Pudong district, a pilot for integrated economic reforms. By the end of 2009, there were 787 financial institutions, of which 170 were foreign-invested. Major capital markets in Shanghai include the Shanghai Stock Exchange, the Shanghai Futures Exchange and the Shanghai Gold Exchange. By 2012, around 60% of Shanghai's GDP came from the tertiary sector, and the remaining part was from high end manufacturing, electronics, and petrochemicals etc. (Lin, 2016). Hence, Shanghai is still a major energy consumer in China, especially in oil consumption, ranked second in 2012, and largest oil consumption sector is transport (see Figure 5.7). However, according to statistics (see Table 5.1), hydropower generation in Shanghai was still 0 by 2012.

Shanghai's pollution level is always lower compared to other large cities in China.[18] But in recent years, public awareness of the environment in Shanghai has grown, and the municipality government is now investing in a number of environmental protection projects, including improving the river water quality and providing incentives for transport companies to purchase eco-friendly LPG buses and taxis (Leung, 2011). Additionally, the government has reallocated almost all the factories with high pollution potential from the city center to either the outskirts or other provinces in recent decades.[19] In addition, Shanghai is also one of China's first carbon emission trading pilots.

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[17] The geographic location introduced by Shanghai Municipal People's Government. Retrieved 14 September 2011.

[18] "Shanghai warns children to stay indoors on haze, PM2.5 surge". Bloomberg News. Retrieved 25 December 2013.

[19] "Environmental protection in China's wealthiest city". The American Embassy in China. July 2001. Archived from the original on 30 October 2007.

Jiangsu

Jiangsu is an eastern coastal province, one of the leading economic development areas in China. According to the latest statistics, Jiangsu has one of the highest GDP per capita of all Chinese provinces, ranked in 4th place in 2015.[20] Jiangsu's economic achievement requires significant energy support. In 2012, Jiangsu's coal, gas and oil consumption were all ranked in the top 5 among 30 provinces in China (see Table 5.4). High energy consumption not only relies on energy imports, but also the abundant coal, petroleum, and natural gas deposits. In addition, even though Jiangsu was also the largest thermal electricity generating province in 2012, unlike Shanxi and Inner Mongolia, it still requires a certain amount of electricity net imports. In recent years, Jiangsu has made some efforts to adjust the its energy consumption structure. For instance, the government made a plan to promote the solar industry and hoped by 2012 that the solar industry would be worth 100 billion RMB.[21] Moreover, Tianwan nuclear power plant construction was finished in May 2007 and commercial operation began in August 2007, which has also made Jiangsu become one of the three provinces in China who have the ability to generate nuclear power.

Jiangsu's terrain is low and flat. It has many rivers and lakes, and the water proportion has continued to be the highest in Chinese provinces.[22] However, because of the geographic characteristics of Jiangsu, the hydropower plants are very few and the scales are small, the total generation amount was only 1,200 million kWh in 2012 (see Table 5.1). Moreover, Jiangsu's forest coverage rate continued the rapid growth and this had increased to 22.5% in 2015. Its forest area has reached 2,955 hectares, and the total volume was 90 million cubic meters.[23]

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[20] According to World Economic Outlook Database April 2016 (IMF-WEO April 2016).

[21] Source from: The China Perspective.`http://thechinaperspective.com/topics/province/jiangsu/`

[22] Quote from the China's National Marine Information Center

[23] Numbers come from the Jiangsu's goverment. `http://www.jiangsu.gov.cn/`

Zhejiang

Zhejiang is an eastern coastal province of China, and the third largest exporter with 3.46 trillion RMB GDP in 2012. As a result of provincial business friendly policies, Zhejiang has witnessed the success of small business clusters, and has achieved a relative small urban and rural income gap in China. Zhejiang's leading manufacturing sectors are electromechanical industries, chemical industries, food, textile and construction materials. The secondary industry and tertiary industry accounts for 47.7% and 47.9%, respectively.[24] Hence, Zhejiang has been one of the top high energy demand provinces in recent years.

Due to Zhejiang's geological conditions, the levels of coal and gas resources are very low. As a result, Zhejiang started Qinshan nuclear plant construction, one of China's earliest nuclear power plants, in 1985 and this began operation in 1994. In addition, two more new nuclear power plants (Fangjiashan and Sanmen) construction are ongoing and are expected to commence operation in 2016 and 2017. In addition, Zhejiang was also in the top five oil consumption regions in 2012. Zhejiang consists mostly of hills, which account for about 70% of its total area, and the forest coverage is 57.41%, according to Figure 5.8.

Anhui

Anhui is an central inland province located across the basin of the Yangtze River and the Huai River. In 2012, Anhui's nominal GDP was 1.72 trillion RMB. Its economy depends greatly on primary industries, which account for 12.7% of total GDP. Compared to neighboring provinces in the eastern area, Anhui has not experienced outstanding rapid economic growth. The demand for energy consumption was not high in 2012. However, because of the rich coal reserves in China (3.51% of total reserves, see Table 5.2), Anhui emphasizes the development of the thermal electricity industry. In 2012, the total thermal power generation was 176.7 billion kWh. Meanwhile, Anhui was also a main electricity exporter in China, with an electricity export volume of around 44.66 billion kWh in 2012.

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[24] Source:`http://www.zj.stats.gov.cn/tjgb/gmjjshfzgb/201502/t20150227_153394.html`

Most of the water systems in the territory of Anhui belong to the Yangtze River and Huaihe River. The water resources are rich, but the hydropower generation is relatively low (only 3,600 million kWh in 2012, see Table 5.1). The forest coverage reached 26.06% in 2012.

Fujian

Fujian is located on China's southeastern coast and is the closet point in mainland China to Taiwan. Fujian's nominal GDP grew 11.4% and reached 1.97 trillion RMB in 2012. Its economy has been a major beneficiary of foreign direct investment, and the main industries include petrochemicals, machinery, electronics and the tourism sector. Fujian's energy supply is sufficient. The hydropower generation was 47.6 billion kWh, and the thermal power generation reached 111.8 billion kWh in 2012. It can also export 4,200 kWh of electricity apart from its own consumption. From 2013 to 2014, the Ningde nuclear power plant began the first stage of its operation, and the other new nuclear power station (Fuqing) has officially started construction and aims to export in the future.[25]

In the aspect of environment, Fujian is considered to be a water rich province. Due to the special geographic structure of many mountains and hills, it has a huge potential regarding water resources and hydropower generation. In addition, Fujian also has high forestry cover in China. In 2012, its forest coverage reached 63.1%, ranked the in first place.

Jiangxi

Jiangxi is located in the southeast of China, and is one of the six provinces in the central economic region.[26] In 2012, Jiangxi's GDP grew about 11% and reached 1.29 trillion RMB. Jiangxi is rich in natural resources. For instance, the deposits of precious metals and rare-earth minerals rank the leading position among the provinces in China.[27] As a

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[25] Source form: http://www.world-nuclear-news.org/

[26] NBSC

[27] See,http://english.jiangxi.gov.cn/aboutjiangxi/factsaboutjiangxi/201504/t20150421_1142803.htm

result, its secondary industry is dominated by metal-related mining, smelting and pressing sectors. It was also a energy net importer with 10.88 billion kWh amount of electricity import in 2012 (see Table 5.4). For the aspect of renewable energy development, Jiangxi has a huge potential of hydropower due to its rich water resources. The Gan River in the territory runs across from the south to the north and flows into the Yangtze River. In addition, it also has ample geothermal energy resources.[28] According to the statistics in 2012, Jiangxi's forest coverage was the highest China at 58.32%. Hence, the carbon emissions amount in Jiangxi also showed a lower level in 2012 (see Table 5.4).

Shandong

Shandong is part of the east coast region of China. It is one of the richer provinces of China. In 2012, Shangdong's nominal GDP grew 9.8% to around 5 trillion RMB. The province's industrial output has been dominated by heavy industry, especially for energy industry related to coal and oil. Nonetheless, Shandong is also a cradle for many national giants in light industry.[29] According to Table 5.4, Shandong was the largest coal consumer in 2012 with a consumption amount of 402.33 million tons. Moreover, even if it was the largest thermal electrical energy producer, it still needed 489.8 billion kWh electrical energy imports to support its huge energy consumption in 2012. In addition, Shandong is also one of the most important oil bases in China. Since 1955 (when Shengli oilfield was discovered), it has played a leading role in China's domestic crude oil production. In 2012, it consumed the highest level of oil around 16.952 million tons, and the majority was used for petroleum refineries inputs (see Figure 5.7). As a result, it also generated the highest level of carbon among all China's provinces. In terms of renewable energy use, Shandong hydropower generation is very low comparatively due to the very limited water resources (only 120 million kWh in 2012, see Table 5.1). But the long coastline of Shandong has also endowed it with strong potential in wind power development.

In order to change the economic development model for energy overdependence, Shandong government has also made significant efforts to improve energy efficiency. For in-

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[28] Source:`http://www.accci.com.au/keycity/jiangxi.htm`

[29] Source from: `http://china-trade-research.hktdc.com/`

stance, in 2011, Shandong obatained a loan from the Asian Development Bank (ADB) to conduct an energy efficiency and emission reduction project, which aimed to promote energy efficiency and emission reduction measures in the province's industry sector, develop energy service companies, and enhance institutional capacity to identify and manage energy efficiency and emission reduction projects.[30]

Henan

Henan is located in the central part of China. Agriculture has traditionally been a pillar of its economy, with the nation's highest wheat output and second highest rice output, earning its reputation as the breadbasket of China. Henan is rich in mineral resources. Its coal reserve accounts for 4.31% of the total national reserve (see Table 5.2), and the Zhongyuan oilfield is one of the largest oilfields in China (see Figure 5.5). Hence, Henan's economic development also depends on energy industry. In 2012, Henan was one of the largest thermal electricity producers and also an important hydropower generator in northern China. Even though Henan was able to generate a large amount of electricity, it was still a net electricity importer in 2012 with 32.97 billion kWh amount of electricity imported. In water resources, Henan's total annual average water reserve is 40.5 billion cubic meters, ranked 19th, and the potential hydropower resources available for development is around 315 kilowatts.[31] In 2012, Henan's forest coverage reached 20.16%.

Hubei

Hubei is located in the central part of China, and lies in the middle reach of the Yangtze River with an area of 186,000 square kilometers.[32] Like many provinces in the central region, Hubei is also an important agriculture province in China, particular for rice products, while its leading industries include the automotive sector, food, steel, and petrochemical industries. In 2012, the nominal GDP was 2.23 trillion RMB.

Hubei is the hydropower base of China. There are over 1,190 rivers with a total length

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[30] Source:http://www.adb.org/projects/40524-013/main

[31] Source:http://www.henan.gov.cn/hngk/system/2011/03/04/010233527.shtml

[32] Source: http://en.hubei.gov.cn/hubei_info/introduction/

of 35,000 kilometers. According to the Hubei government statistics, the developable installed capacity of hydro energy has reached 33,570,000 kilowatt, ranking at the fourth throughout the country.[33] Currently, the Three Gorges Hydropower Plant in Yichang city of Hubei is the largest hydropower plant in the world in terms of installed capacity (22,500 MW). It plays an important role in flood control, electricity generation, shipping and tourism. A number of large hydropower plants are also located in Hubei, namely Gezhouba, Geheyan and Danjiangkou.[34]

In terms of its emissions trading program, Hubei is also one of the first pilots and started to implement an emission trading system from 2014.

Hunan

Hunan is located in South Central China, and south of the middle course of the Yangtze River. Hunan is traditionally a rice and cotton growing area in China but machinery, steel, and food processing are now also major contributors to its industrial output. In 2012, its nominal GDP was 2.22 trillion RMB. Hunan has an extensive network of rivers, and has the largest reserve of natural water resources among the provinces of southern China. There are four main tributaries of the Yangtze River flowing through Hunan. Hence, rich water resources advantages can promote the development of hydroelectric power. Furthermore, Hunan has abundant resources of animals and plants. There are around 5,000 species of seed plants, ranking it 7th across the country. There are more than 2,000 species of woody plants, and 1,000 species of wild economic plants.[35] In 2012, the forest coverage reached 44.76%.

Guangdong

Guangdong is located in China's southeast corner, and belongs to the east coast economic area. Since 1989, Guangdong has topped the GDP ranking among all provinces in main-

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[33] Source: `http://en.hubei.gov.cn/hubei_info/introduction/geography/`

[34] Source: `hubei.gov.cn`

[35] Source:`http://www.enghunan.gov.cn/AboutHunan/HunanFacts/NaturalResources`

land China. In 2012, its nominal GDP reached 5.71 trillion RMB. It is not only China's largest exporter of goods but also the largest importer. Recently, Guangdong has also led the way in moving up the manufacturing value chain from light industry production to high end manufacturing of goods like IT products and power equipment. Hence, the strong economic growth of Guangdong requires a huge amount of energy to support. In 2012, Guangdong generated 284.8 billion kWh of thermal electricity, ranked in the top five in thermal energy production despite its coal reserve only accounting for 0.01% in China's total reserves (see Table 5.2). It was also the second largest gas consumer and the third oil consumer in 2012 (see Figure 5.4 and 5.7). In the renewable energy aspect, Guangdong also produced the largest nuclear power. However, it was still China's largest electricity net importer with 97,500 million kWh imported in 2012. In recent years, the nuclear power development plan has seen as very important for the government to solve Guangdong's growing energy demand. The construction of two new nuclear power plants (Yangjiang and Taishan) have been started since 2008 and 2009, and these plants are expected to be completed in 2014 and 2015, respectively.

Guangdong's forest resources are abundant. In 2012, its forest coverage was 49.44%. As a major energy consumption province, Guangdong has also been listed as one of the first carbon emission trading pilots since 2013.

Guangxi

Guangxi is officially the Guangxi Zhuang Autonomous (province-level) Region, located in southwest China, and belongs to the western economic area. Tourism and food processing are major industries for Guangxi's economy, and it has not developed a significant manufacturing base. In 2012, Guangxi's nominal GDP was 1.3 trillion RMB. Hence, its energy demand is relatively lower compared to other similar sized provinces. In 2012, it produced 64.7 billion kWh of thermal electricity and only consumed 318 million cubic meters of natural gas, the lowest amount among 30 provinces in China (see Table 5.4). On the other hand, Guangxi has abundant water resources. The Pear River basin area in Guangxi territory is 202,400 kilometers square, accounting for 85.2% of the total area in Guangxi.[36] Therefore, rich water resources may result in a considerable scale of hydropower generation. In 2012, Guangxi produced 52.4 billion kWh of hydroelectrical energy. Moreover, Guangxi was also rich in forest resources with forest coverage reaching 52.71% in 2012.

Hainan

Hainan is the southernmost island province of China. The tropical climate makes the province an important source of paddy rice, tropical fruits, and fisheries. The main economic drivers of Hainan are tourist related services and agriculture, and secondary industries such as automobile equipment also constitute a small portion of its economy. In 2012, Hainan's GDP reached 285.53 billion RMB. Hainan's total coal consumption was the least and thermal energy production was the second lowest among 30 provinces in 2012. But it also generated 2.4 billion kWh hydropower and 400 wind power, which made a balance between electricity production and consumption without any imports and exports (see Table 5.4). In addition, Hainan is rich in tropical plant resources. In 2012, its forest coverage reached 51.98%, ranked 4th in China.

Chongqing

Chongqing is a major province-level city in southwest China, and one of the four direct-controlled municipalities (the other three are Beijing, Shanghai and Tianjin). Chongqing's export sector is small unlike eastern China due to its being inland. Instead, factories producing local-oriented consumer goods such as processed food, motor vehicle, chemicals, machinery and electronics are common. Chongqing's nominal GDP in 2011 reached 1 trillion RMB. Moreover, massive government support is transforming Chongqing into the region's economic, trade, and financial centre, which may then open up China's western interior to further development. Many rivers and water systems crisscross the territory of Chongqing, and they have tremendous potential energy to be developed. According to the statistics from the Chongqing government, the annual water resources reach 500 billion

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[36] Source:`http://www.gxzf.gov.cn/zjgx/gxrw/zrdl/201603/t20160331_486081.htm`

cubic meters. The city has 14.38 million kilowatts of water energy in theory, of which 7.5 million kilowatts can be developed. This also makes Chongqing one of the top cities in China in terms of water energy.[37] Chongqing's forest coverage was 34.85% in 2012 while it is also one of the first carbon emission trading pilots.

Sichuan

Sichuan is a province of southwest China, and one of the major agriculture production bases in China. It is also a major industrial centre, with industries like coal, energy, iron and steel. In 2012, Sichuan's nominal GDP was 2.38 trillion RMB. In terms of energy utilisation, Sichuan plays an important role in energy production due to the largest proven reserve of natural gas in the Sichuan basin (see Figure 5.3), and it was also the largest gas consumer in 2012 with 15.3 billion cubic meters, accounting for 10.19% in total gas consumption in China (see Figure 5.4). Meanwhile, Sichuan is also a major hydropower generation province. Abundant water resources provide a strong guarantee for its hydropower development. In 2012, it produced the largest amount of hydroelectricity among the 30 provinces. However, a significant amount of energy is not only for its own consumption, but also for exporting to other provinces, especially to eastern developed regions. In 2012, around 11.94 billion kWh of electricity was exported to other areas.

Guizhou

Guizhou is a province located in the southwestern part of China. It is considered as one of China's poorest provinces and it relies heavily on agriculture and tourism to drive its economy.[38] In 2012, Guizhou's nominal GDP was 680.2 billion RMB. However, Guizhou has significant coal reserves, accounting for 3.02% in total China's coal reserve (see Table 5.2). Hence, power generation has become its important industry sector. In 2012, Guizhou produced 104.6 billion kWh of thermal electricity, and also generated 56.49 billion kWh of renewable electrical energy (see Table 5.4). However, a certain amount of electricity is produced to export to Guangdong and other eastcoast provinces. Guizhou's climate is

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[37] Source:http://en.cq.gov.cn/AboutChongqing/2007/6/12/981921.shtml

[38] Source: http://thechinaperspective.com/topics/province/guizhou/

warm and humid and the forest coverage reached 31.61% in 2012.

Yunnan

Yunnan is a province located in the southwest part of China, and it is also the largest tobacco base in China. The main manufacturing industries include iron and steel production and copper-smelting, due to its significant metal resource reserves. In 2012, Yunnan's nominal GDP reached 1.03 trillion RMB. Yunnan's gas and oil consumption is very low. In 2012, its gas consumption was only 430 million cubic meters, ranked as the second last among 30 provinces, while oil consumption was only 26,100 tons, ranked 27th out of 30 provinces (see Table 5.4). However, Yunnan's water resources are abundant. According to government statistics, the whole province's water energy reserve is 104.37 million KW, accounting for 15.3% of national total hydropower reserves, and the theoretical exploitable installed capacity could be 97.95 million KW, ranked second in China.[39] In 2012, Yunnan's total hydropower generation was 124 billion kWh, and it was also a very important electricity exporter. Unlike the other energy exporters in China, Yunnan's electricity exports mostly come from the environmentally friendly hydropower generation.

Shaanxi

Shaanxi is a province, located in northwest China. The fossil fuel production and high technology sectors are the two largest industries in Shaanxi. In 2009, Shaanxi ranked third in China for producing 296 million tons of coal, and 18.95 billion cubic meters of natural gas.[40] In addition, it also played an important role in China's aircraft and aerospace industries. In 2012, Shaanxi's nominal GDP was 1.45 trillion RMB. In terms of coal use and thermal energy production, Shaanxi has 4.74% of the reserves of coal resources in China. In 2012, it consumed around 157.74 million tons of coal, and produced 114,900 million kWh of thermal electricity. Table 5.4 also shows that Shaanxi was an electrical energy net importer in 2012. Due to the serious geographical imbalance features in the distribution of Shaanxi's water resources, the hydropower generation is limited. In 2012,

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[39] Source: `http://www.yn.gov.cn/yn_yngk/index.html`

[40] Source: `http://thechinaperspective.com/topics/province/shaanxi/`

the total hydropower generation was 8.1 billion kWh. According to the survey from the National Bureau of Statistics of China, the forest coverage in Shaanxi was 37.26% of its total area.

Gansu

Gansu is located in the western part of China. It is bordered in the north by the Gobi Desert and in the south by the Qilian Mountains (Guo et al., 2015). It has one of the harshest climates and it is also one of the most undeveloped provinces. Due to its unfavorable climate, Gansu does not seem easy to attract companies and individuals to operate businesses and live. In 2012, its nominal GDP was 565 billion RMB. However, because of the climate in Gansu as well, it is considered an ideal place for solar power generation and wind farms. In 2012, 9.4 billion kWh of wind power energy was generated by Gansu, ranked 3rd among 30 provinces. In terms of natural resources, Gansu's forest resources are relatively scarce. In 2012, the forest coverage only accounted for 10.42% of the province's total area.

Qinghai

Qinghai is a province of China located in the northwest of the country. In 2012, its nominal GDP was only 188.45 billion RMB. Although Qinghai is largely undeveloped outside of its capital, it is rich in natural resources and its economy heavily depends on minerals and hydropower. Qinghai also plays an important ecological role in China as it is the source of many rivers like the Yellow River and the Yangtze River. In 2012, its hydropower generation reached 45.8 billion kWh (see Table 5.1). Furthermore, Qinghai also has one of China's major natural gas fields (Qaidam Basin) (see, Figure 5.3). Hence, the energy sector in Qinghai always makes a significant contribution to its economy. Another notable feature of Qinghai is the lack of forest resources. In 2012, the forest coverage only accounted for 4.57% of its total area.

Ningxia

Ningxia is a province, located in the northwest part of China, which is a neighbour to Inner Mongolia and Shaanxi. Compared to its neighbours, Ningxia's economic fundamentals are relatively weak. Lacking in natural resources, Ningxia still focuses on its agricultural sector to prevent against natural calamities such as a dry climate, shortage of water, and sand storms. In 2012, Ningxia's nominal GDP was only 232.66 billion RMB, and its hydroelectrical energy generation only reached 1,900 kWh (see Table 5.1). In terms of forest resources, Ningxia's forest coverage was only 9.84% in 2012.

Xinjiang

Xinjiang is an autonomous region located in the northwest of China. It is the largest Chinese administrative division but only about 4.3% of Xinjiang's land area is fit for human habitation.[41] Xinjiang's GDP nearly doubled from 2004 to 2009 and increased 12% to 753.03 billion RMB in 2012. It has recently become one of the important energy producers and exporters in China. Two main natural gas fields (Junggar and Tarim Basins, shown in Figure 5.3), and a large oil field (see Figure 5.4) have been discovered and exploited in Xinjiang. Although the discovery of natural resources has undoubtedly been a boost for the province, these resources are still scattered about an uninhabited landscape. Hence, in the production and development of the transport sector it will be necessary to take advantage of economic growth in this region. On the other hand, Xinjiang is also rich in solar and wind energy resources thanks to the geological conditions. The local government has recently made a series of solar energy development plants to attract the new investment to this area.

Xinjiang's forest resources are scarce. In 2012, the forest coverage was only 4.02%, ranked the last among 30 provinces in China.

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[41] Source:`http://en.people.cn/english/200006/09/eng20000609_42636.html`, People's Daily.

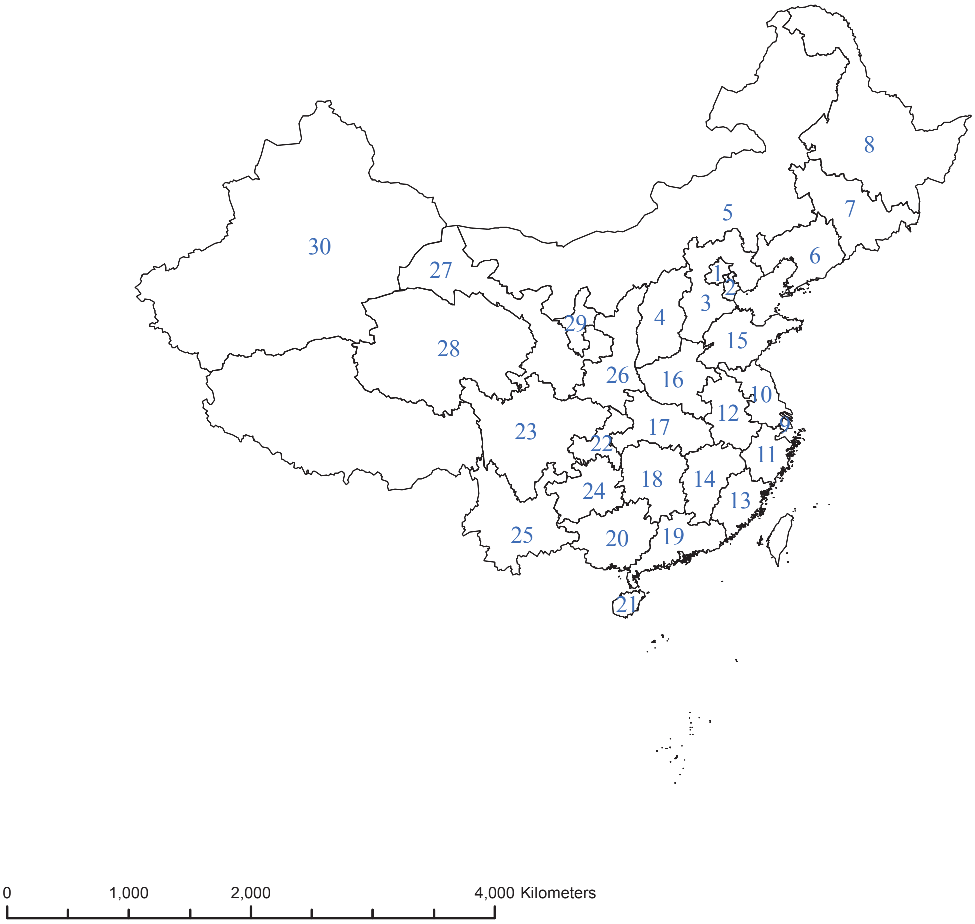
5.3 Policy Analysis Incorporating Results in Chapter 4 and Regional Profile

The major carbon emissions in China are coming from the thermal power plants. Some larger thermal power producing provinces are highlighted in this chapter. The huge energy demands for Jiangsu, Shandong, Guangdong and Zhejiang result in their leading thermal power generation, and some provinces like Inner Mongolia and Shanxi can also generate high levels of thermal power due to their abundant coal resources. Our MACs estimation under LVES-1 in chapter 4 show MACs in these provinces are relatively low. For example, MAC of Inner Mongolia is only 98.10 USD/tC, ranked the last place (30th) in thirty provinces. MACs of Guangdong and Jiangsu, which have top large size of GDP and huge demand of energy, are 153.09 USD/tC and 195.14 USD/tC, ranked 28th and 27th, respectively. Hence, top generators of thermal electricity are always have lower MACs. Such findings can be exploited by the related local governments to meet their more stringent emission reduction targets due to the currently lower MACs in these provinces with high amount of thermal electrical energy. Furthermore, optimal efficiency-improving reforms calculation in chapter 4 suggest all provinces should decline the thermal coal usage, and the larger thermal electricity generators, like Shandong, Shanxi, Inner Mongolia and Hebei, should decrease the total thermal power generation levels as well. In the aspect of energy utilisation from renewable resources, our efficiency-improving reforms seems to better capture the observed province features. Because the distribution of China's water resources are extremely unbalanced, the southwest areas are much richer than north part of China, which lead to Sichuan, Hubei and Yunnan become the highest hydropower generating provinces. The practical transition from coal-fired plants to hydropower energy could be achieved in those provinces with advantage in water resources and mature technologies. For instance, our efficiency-improving reforms in chapter 4 recommend Hubei, Sichuan, Chongqing, and Yunna to significantly increase the current renewable electrical energy production level, which could be achieved due to abundant water resources in these provinces. Other provinces with limited water resources may search for more feasible options such as development of gas-fired power plants and nuclear stations, which programs have also been in process in some provinces, like Guangdong, Jiangsu and Shandong, etc. In addtion, the uneven distribution of forest status-quo in China is discussed in this chapter. Land in China is either state-owned or collectively-owned. Hence, governments at all levels will play important roles to further improve the management of planation forestry in a long term, especially for the lower forest covered regions. Lastly, the implementation of the carbon emission scheme in several China's target regions has been briefly reviewed. Some pilots, as Beijing, Tianjin, Shanghai, and Chongqing, firstly established a carbon emission reading scheme recently, and these province-level regions are happen to be the relatively higher MAC regions according to our estimation in chapter 4. Hence, even though carbon trading scheme in China still face many technical problems, it seems to be a very important supplement to existing environmental regulations, which allows emission reductions to be first made in locations where the marginal costs of abatement are lowest.

5.4 Conclusions

This chapter overviews China's regional variations in electricity generation, primary energy usage, and forest cover. According to China's regional profile, we study the relevance of the efficiency-improving reforms and MACs estimated in Chapter 4 for the nature of input resource reallocation and its implications for province-level governmental policies. For most provinces in China, the final consumption increasing and emission non-increasing optimal reform recommends decreasing usage of coal in thermal power plants, and increasing renewable energy and non-electrical energy from coal, gas, and oil. Our finding about efficiency-improving reforms seem to capture more details of observed province-specific features and consistent with the development plans of many regions in China. Furthermore, currently China's carbon emission trading system has been implemented only in several pilot provinces at the firm level, rather than on a national scale. Given the great variations in MACs across provinces that we have estimated in Chapter 4, we believe that setting up emission trading between provinces themselves can help achieve China's overall emission reduction target in a least costly way.

Appendix



Source: National Bureau of Statistics of China

Region label: 1-Beijing, 2-Tianjin, 3-Hebei, 4-Shanxi, 5-Inner Mongolia, 6-Liaoning, 7-Jilin, 8-Heilongjiang, 9-Shanghai, 10-Jiangsu, 11-Zhejiang, 12-Anhui, 13-Fujian, 14-Jiangxi, 15-Shandong, 16-Henan, 17-Hubei, 18-Hunan, 19-Guangdong, 20-Guangxi, 21-Hainan, 22-Chongqing, 23-Sichuan, 24-Guizhou, 25-Yunan, 26-Shaanxi, 27-Gansu, 28-Qinghai, 29-Ningxia, 30-Xinjiang

Figure 5.10: Study Regions in China Map

Table 5.4: Regional Information in 2012

Region	id	Coal cons*	Gas cons*	Oil cons*	Carbon emis*	Thermal gen*	Renewable gen*	Electricity cons*	Electricity ni*	Afforestation*	Location**
Beijing	1	2270	92.07	78.16	5462.60	283	10.1	912	618.9	35.75	E
Tianjin	2	5298	32.58	122.33	6246.45	582	4.7	767	180.3	5.35	E
Hebei	3	31359	45.13	24.53	23020.85	2178	136	3078	764	312.36	E
Shanxi	4	34551	37.39	1.2	14715.08	2454	80	1766	-768	302.85	C
Inner Mongolia	5	36620	37.84	16.91	15057.54	3029	313	2017	-1325	781.61	W
Liaoning	6	18219	63.72	422	17903.75	1345	143	1900	412	246.66	N
Jilin	7	11083	22.79	34.11	7186.31	591	123	787	73	28.16	N
Heilongjiang	8	13965	33.68	99.53	9709.09	772	69	828	-13	162.29	N
Shanghai	9	5703	64.38	640.15	8646.71	967	6.3	1353	379.7	1.16	E
Jiangsu	10	27762	113.14	158.35	21955.42	3943	211	4581	427	57.34	E
Zhejiang	11	14374	48.08	328.67	13756.19	2273	573.8	3211	364.2	43.92	E
Anhui	12	14704	24.9	11.08	8643.66	1767	40.6	1361	-446.6	43.78	C
Fujian	13	8485	37.49	186.3	8512.01	1118	504	1580	-42	98.04	E
Jiangxi	14	6802	10.04	29.85	5504.45	610	149.2	868	108.8	138.64	C
Shandong	15	40233	67.23	1695.2	29602.91	3241	64.2	3795	489.8	197.95	E
Henan	16	25240	73.92	13.16	17995.83	2465	131.3	2926	329.7	228.29	C
Hubei	17	15799	29.28	104.29	13451.02	863	1382	1643	-602	198.57	C
Hunan	18	12084	18.79	61.23	12742.51	765	448.7	1582	368.3	404.23	C
Guangdong	19	17634	116.48	434.91	22179.16	2848	796	4619	975	107.51	E
Guangxi	20	7264	3.18	49.72	6967.13	647	524.8	1154	-17.8	148.87	W
Hainan	21	931	47.49	39.06	1284.60	182	28	210	0	17.73	E
Chongqing	22	6750	70.98	9.89	7060.74	336	210.8	723	176.2	206.21	W
Sichuan	23	11872	153	75.21	15657.98	584	1545.4	2010	-119.4	112.15	W
Guizhou	24	13328	5.26	4.68	7517.35	1046	564.9	1047	-563.9	147.70	W
Yunnan	25	9850	4.3	2.61	7940.48	480	1268	1314	-434	544.46	W
Shaanxi	26	15774	65.97	0.09	8086.59	1149	83.6	1067	-165.6	320.28	W
Gansu	27	6558	20.28	9.25	5332.46	666	438	995	-109	177.33	W
Qinghai	28	1859	40.11	0.17	2681.83	120	458.2	602	23.8	135.64	W
Ningxia	29	8055	20.48	20.62	3471.77	952	52	742	-262	94.81	W
Xinjiang	30	12028	101.95	8.06	9003.62	998	189	1152	-35	210.24	W

Source: China Statistical Yearbook, China Energy Statistical Yearbook, China Electric Power Yearbook and this study.

[*] Unit of Coal and Oil cons (consumption) is 10000 tons. Unit of Gas cons is 100 million cubic meters. Unit of Carbon emis (emission) is 10000 tons. Unit of Thermal and Renewable gen (power generation) is 100 million kWh. Electricity cons and ni (net import) is 100 million kWh. Unit of Afforestation is 1000 hectares.

[**] E, C, N and W represent Eastcoast area, Central area, Northeast area, and West area of China in Location column.

Chapter 6

Conclusion

In this thesis we have mainly studied three important issues that are often studied in environmental economics in the context Chinese provinces, namely, measuring production and environmental efficiency, designing allocative efficiency-improving input policy reforms, and estimating marginal abatement costs.

In the second chapter of this thesis, we introduce by-production approaches to modeling emission generating technologies, and employ the modified HYP and FGL efficiency indexes under the by-production approach to investigate China's regional technical efficiency with due consideration being given to generation of pollution by provinces. By classifying thirty provinces of China into four economic areas, we find the Eastcoast area has achieved the preeminent high efficiency score in the intended output generation. Meanwhile, the West area shows the worst performance in both production and environmental efficiency levels. Through conducting regression analysis, we also find the FGL environmental efficiency is significantly affected by SO_2 abatement activities and energy intensity, but the current environmental regulations may not be playing effective roles in the environmental efficiency scores improvement. Based on our findings, we also indicate that the environmental policy makers should pay more attention to regions with lower technical efficiency. In particular, changing the industrial structure from high energy intensive sectors to high value-added service sectors may achieve environmental efficiency improvement in the long term. Furthermore, improving the existing pollution charge system and environmental standards requires more theoretical study and stricter enforcement. The conclusions of this chapter are also similar to the conclusions of the following chapters that study regional differences in allocative inefficiencies and marginal abatement costs.

The third chapter provides a theoretical methodology to compute the optimal efficiency-improving local reforms and to empirically test the existence of several efficiency-improving local reforms at status-quo. We also derived a measure of marginal abatement cost in the framework of local policy reforms, which can be calculated by using data prevailing at status-quo. In addition, hypotheses about different structures of efficiency-improving reforms can be tested as well by using the methodology developed in conjunction with the data available.

In the fourth chapter, the key features of energy are identified and incorporated in the intended output function modelling. A new class of intended production functions for electrical energy generation and the energy-using sector that treats energy as an intermediate input is specified and two such production functions are estimated along with conventional production functions such as the Cobb Douglas and the CES. We also apply China's province-level data to compute the optimal efficiency-improving reforms and marginal abatement costs based for various specifications in the intended output producing sectors. Our results can be summarised as follows: firstly, our results on measurement of MACs and efficiency-improving reforms are sensitive to the functional forms used. Secondly, under all functional specifications, MACs vary across all provinces, but Beijing always has the highest MAC. Provinces with high thermal electricity generation have a lower level of MACs. Lastly, the optimal reforms under LVES-1 production function relate more to province specific features. For provinces with intensive coal mining sectors, the optimal reforms recommend decreasing thermal energy generation primarily by reducing usage of coal. For all provinces, the efficiency will increase the most when all provinces increase renewable electrical energy generation and switch from coal-fired plants to gas-fired plants.

The fifth chapter reviews China's regional profile of energy, forests, and carbon emission trading scheme. We find that the policy recommendations of the reforms we propose in Chapters 3 and 4 seem consistent with the development plans of many regions in China. The final consumption increasing and emission non-increasing can be achieved by decreasing usage of coal in thermal power plants, increasing electrical energy generated by gas-fired plants, and increasing renewable energy and non-electrical energy from coal, gas, and oil for most provinces. In addition, given the great variations in MACs across provinces that we have estimated in Chapter 4, we think that setting up emission trading on a national scale can help achieve China's overall emission reduction target in a least costly way.

In terms of further studies, we would like to make more efforts to improve our dataset in Chapter 4. For instance, we use the share of fixed assets to estimate the proportion of capital stock in electricity generation industries for each provincial region, and use the share of installed capacity to estimate the proportion of capital stock in coal-fired plants and renewable energy plants. Such treatment can approximately capture the variation of capital use for energy sectors in different province. If we could find more accurate capital stock data resource for each province in China, our results will be improved. Similarly, data on allocation of labour in thermal and renewable energy was only available in 2011 from China's official released data resources, we have to estimate the ratios of labour use in rest of study period based on the ratio in 2011. Even though we believe the employment ratio of a region's energy sector in China would not change a lot in the short term, more accurate data is still desirable. Furthermore, when we model the gas-fired electrical energy and non-electrical energy generation, we apply the concepts of heat rate, efficiency conversion and levelised costs as data on labour and capital employed in these sectors is not available to estimate production functions for these sectors. Even to estimate the levelised costs, heat rates, and energy factors in these sectors, we have to rely on sources such as the REMIND model from Luderer et al. (2015), rather than on estimates based directly on China. Since the gas-fired electricity generation and renewable energy utilisation in China are still at an early stage, some more empirical studies are required to provide more accurate estimates that will help us build more detailed models and improve the accuracy of our results. On the other hand, China ranks second in the world, next only to USA, in terms of the physical volume of afforestation. Hence, the role of afforestation in efficiency improvement in China needs to be explored further with better province-level estimates of carbon sequestration factors for forests. Given the differences in type and coverage of forests across provinces, sequestration factors vary a lot. At the moment, the research is using an overall China estimate that leads to afforestation playing a very limited role in the optimal efficiency-improving reforms. It is significant only for Beijing. It is also worth noting that, the necessary afforestation area for each region in order for the policy to be feasible seems to be calculated for each region. However, carbon emission is a global pollutant so the sequestration effect seems to take the whole countries's afforestation area as consideration. Since the s coefficient differs between regions, an additional optimisation should be undertaken to determine the optimal location of afforestation for China as one unit. Hence, this issue may be suggested as future research. Lastly, in terms of the new production functional specifications (LVES) we proposed in Chapter 4, it is worth noting that though they capture some of our intuition regarding production relations in energy-using and energy-generating sectors, both LVES-1 and LVES-2 imply that any pair of inputs are highly complementary. In our future research, a new direction could be to explore more general LVES production specifications that allow for greater variation in elasticities of substitution including allowing for pairs of inputs like labour and capital to be substitutable.

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