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Analyzing the Regional Impact of a Fossil Energy Cap in China

Da Zhang[*†§], Valerie Karplus[*], Sebastian Rausch[*‡§], and Xiliang Zhang[†]

Abstract

Decoupling fossil energy demand from economic growth is crucial to China's sustainable development. In addition to energy and carbon intensity targets enacted under the Twelfth Five-Year Plan (2011–2015), a coal or fossil energy cap is under discussion as a way to constrain the absolute quantity of energy used. Importantly, implementation of such a cap may be compatible with existing policies and institutions. We evaluate the efficiency and distributional implications of alternative energy cap designs using a numerical general equilibrium model of China's economy, built on the 2007 regional input-output tables for China and the Global Trade Analysis Project global data set. We find that a national cap on fossil energy implemented through a tax on final energy products and an energy saving allowance trading market is the most cost-effective design, while a regional coal-only cap is the least cost-effective design. We further find that a regional coal cap results in large welfare losses in some provinces. Capping fossil energy use at the national level is found to be nearly as cost effective as a national CO_2 *emissions target that penalizes energy use based on carbon content.*

Contents

1. INTRODUCTION

In the search for policy approaches to address environmental, climate, and health damages from fossil energy use, China has been the first country to propose capping the use of coal and

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other fossil fuels directly.[1] While the precise features of the cap have yet to be determined, policymakers have suggested that the cap will restrict primary consumption of coal to 3.9 billion tons of coal equivalent in 2015, compared to 3.5 billion tons used in 2011 (Kraemer, 2012; National Development and Reform Commission, 2012).[2] It is not clear whether or not this cap will be difficult to meet, as it depends on the rates of China's economic growth and energy intensity improvement. If the high growth rates (greater than 10%) of recent years persist, keeping the rate of increase in coal use to less than 3% per year will require a significant reduction in the intensity of coal use. Given the potentially central role of an energy cap in China's future climate policy, this analysis investigates the cost effectiveness and distributional impact of a coal or fossil energy cap as an energy use and carbon dioxide (CO_2) reduction strategy.

Recent policy discussion has centered on whether a cap should restrict the use of coal only or restrict all fossil energy sources. Advocates of a coal cap argue that coal is the appropriate policy target because the environmental and health externalities of coal use are the most detrimental, and because there is a history of setting specific goals for coal capacity and use. Constraining all fossil sources, by contrast, would allow energy reductions to come from the natural gas, oil, and coal sectors. Since fuels are not differentiated based on carbon content under an energy cap, there is concern that capping all fossil sources might perversely result in a situation where relatively cleaner natural gas is reduced at the expense of continued reliance on coal. By simulating both types of caps in a numerical energy-economic general equilibrium model and comparing them to a national cap on CO_2 embodied in energy, we investigate the existence and magnitude of such effects, and to compare the relative efficiency of different policy designs.

China's economy and energy system are characterized by significant heterogeneity—coal production is concentrated in the northern and western regions, while demand for electricity and energy for industrial processes is highest along the more prosperous eastern seaboard. The availability of low carbon substitutes for fossil energy such as hydropower and wind are also regionally determined. The country's western provinces, in contrast to those in the east, are less affluent and, while they are major suppliers of energy, they use relatively less total energy and use energy less efficiently, in part due to reliance on inefficient production technology and in part due to their economic structures (Liu *et al.*, 2012). Policymakers broadly agree that climate policy should not exaggerate these regional disparities, and if possible should accelerate sustainable development and technological upgrading in lagging regions. In this analysis we are able to investigate how the impact of a coal or energy cap would be distributed, and if alternative policy designs could help to improve overall cost effectiveness and minimize undesirable distributional impacts.

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[1] A cap could take the form of a constraint on coal use or other forms of fossil energy. Although often simply referred to as an energy cap, the policy under consideration exempts energy types with no associated carbon footprint, such as nuclear and renewable energy. The cap would limit on an energy basis the total fossil energy use, which in China is typically measured in metric tons of coal equivalent (Xinhua Press, 2011).

[2] The Twelfth Five-Year Plan's Coal Industry Development Plan assigns a target for China's coal production capacity of 4.1 billion tons, but a target for coal consumption of 3.9 billion tons in 2015.

This paper is organized as follows. Section 2 provides background and context for analyzing an energy cap policy in China, reviewing the current policy discussion and important policy design considerations. Section 3 discusses regional energy and economic system characteristics across China's provinces, providing a basis for interpreting the comparison of policy scenarios. Section 4 describes the model used in this analysis. Section 5 presents the results of the analysis, focusing on the cost effectiveness and distributional impacts of alternative policy designs. Section 6 discusses the implications of the results for policy design decisions, which in practice will inevitably weight cost effectiveness against the political feasibility of various options.

2. CONTEXT FOR ANALYZING AN ENERGY CAP POLICY IN CHINA

2.1 Energy Cap Background

Most of the discussion around limiting energy use in China has focused on coal (Point Carbon, 2012). Coal supplied around 77% of Chinas primary energy demand in 2010 (National Statistics Bureau, 2011b). Coal also has the highest carbon content of all fossil fuels and has been responsible for localized air and water pollution as well as severe health consequences across China (Matus *et al.*, 2012). The notion of a coal cap is actually not new, and dates back to historical practice of production targets chosen within the context of China's planned economy. In China's recent five-year plans, the stated coal consumption target has been consistently exceeded but is still considered as an important policy instrument (Zhang *et al.*, 2012b). In the Twelfth Five-Year Plan (2011 to 2015), a target for coal use at the national level has been set, restricting primary consumption to 3.9 billion tons in 2015. This cap would be implemented through targets set at the provincial (or even sub-provincial levels), as it is established practice in China's administrative system to explicitly assign responsibility for meeting national targets to individual provinces. Several provinces and municipalities have already announced a cap on coal for the Twelfth Five-Year Plan (People's Daily Online, 2011; 21st Century Business Herald, 2011; Xinhua Press, 2011).

Recently, policymakers have discussed replacing or complementing the existing coal cap with a fossil energy cap, with the objectives of curbing energy use, reducing CO_2 emissions, and improving air quality and health. While a target would be assigned at the national level (Lan, 2012; Reuters, 2012), this proposal is also likely to include the allocation of targets at the provincial level. There are no reports that any allowance trading mechanism has been discussed in relation to a coal or fossil energy cap, although in policy discourse a fossil energy cap has been discussed as a step toward the development of a national cap-and-trade system.

Another design question is whether the cap will restrict primary energy or final energy in order to achieve a targeted reduction in total energy use—in all existing energy cap proposals to date, primary energy is the target. Primary energy may be easier to target than final energy in the current institutional setup, given that oversight involves controlling fewer entities, many of which have direct links to national or provincial governments. Targeting final energy demand would allow reductions to be achieved by limiting both local primary energy and imported energy embodied in final demand. Economic intuition would suggest that broader coverage—i.e.

including all fossil energy sources, allowing trading under a national cap, and targeting reductions in final rather than primary energy demand—would be the most cost-effective approach, given that it maximizes abatement flexibility. However, implementing these provisions will require some changes in China's institutional environment that could prove difficult to implement on a short time frame or lack the support necessary to be implemented effectively. In this context, it is important to understand both the efficiency penalties associated with moving to less flexible policy designs as well as the distributional implications.

An investigation of the cost effectiveness and distributional impacts of various energy cap policy designs requires a model that captures in a single framework sufficient detail in China's energy and economic system at the regional level. It must also capture interactions across multiple markets and endogenous changes in prices and income, given that an energy cap would bear on one or more energy commodities that are inputs to a large number of sectors across the economy. We therefore employ a regional computable general equilibrium model of China that represents economic flows as well as energy demands and associated CO_2 emissions as supplemental physical accounts. This model allows us to assess the full range of policy design combinations and compare their effects on energy use, CO_2 emissions, and the economy at the national and provincial levels. Our outputs are intended to supply a cost-effectiveness comparison that can be considered alongside political feasibility and other criteria in the policy design process.

2.2 Literature Review

Our analysis of the coal cap contributes to a rapidly growing literature on the design of energy and climate policy in China (Zhang, 1998, 2000; Cao *et al.*, 2009; Li *et al.*, 2009; Cong and Wei, 2010; He *et al.*, 2010; Lu *et al.*, 2010; Zhao and Ortolano, 2010; Dai *et al.*, 2011; Zhang *et al.*, 2011; Zhou *et al.*, 2011; Wei *et al.*, 2012; Zhang *et al.*, 2012a). Methodologies used to evaluate policies vary widely, from system dynamics modeling (Cong and Wei, 2010) to CGE modeling (Zhang, 1998; He *et al.*, 2010; Dai *et al.*, 2011; Zhang *et al.*, 2012a) to qualitative investigation (Zhao and Ortolano, 2010; Zhang *et al.*, 2011). Many studies use observations of regional energy intensities and abatement costs to inform the design of environmental policy in China (Zhou *et al.*, 2011; Wei *et al.*, 2012). Other scholarship has focused on how differences in abatement potential and costs across provinces can be used to determine how reduction targets are assigned. Wei *et al.* (2012) provides estimates of abatement potential and costs for 29 provinces, with the goal of balancing efficiency and equity concerns through the assignment of targets and in the absence of an inter-provincial trading mechanism.

Given the importance of understanding the consequences of policy design choices for regional energy use, emissions, and economic activity, we focus on the role of three salient policy design choices currently under discussion—whether to cap coal only or all fossil energy sources, whether to assign targets based on primary or final energy consumption, and whether to assign targets at the national or regional level. Specifically, we are interested in understanding the consequences of targeting primary or final energy use to achieve the intended reductions, an issue discussed at length in (Bushnell, 2011). We are also concerned with the consequences of assigning regional (e.g., provincial) or national targets, which was considered for the case of China in a study of CO_2 intensity target design (Zhang *et al.*, 2012a). Our investigation contributes to the literature on energy and climate policy design in China by simulating a full range of alternative energy cap designs in a comprehensive energy-economic framework. Given that addressing climate change is an important policy objective, we further compare simulated energy cap policy designs to a cap on CO_2 emissions.

3. HETEROGENEITY OF ENERGY USE ACROSS CHINA'S PROVINCES: A MULTI-REGIONAL INPUT-OUTPUT ANALYSIS OF EMBODIED ENERGY

3.1 Data and Methodology

To develop intuition to assist in interpreting the results of the policy analysis, we undertake an empirical assessment of embodied energy use across China's provinces. This analysis is based on an energy-economic data set that includes a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade for the year 2007. The data set is based on detailed provincial-level data for China and a global economic and energy data set. Data for China is based on the full set of China's recently published 2007 provincial input-output (IO) tables for all 30 provinces[3] and China's national IO table (National Statistics Bureau, 2011a). The IO tables for each province differentiate 42 sectors, and include data on various existing tax rates in the Chinese economy. The global data is based on the GTAP database (GTAP, 2012), version 8, which identifies 129 countries and regions and 57 commodities, providing consistent global accounts of production, consumption and bilateral trade as well as consistent accounts of physical energy flows, energy prices and emissions in the year 2007. Energy use and emissions data are based on data from GTAP (GTAP, 2012) and the 2007 China Energy Statistical Yearbook (National Statistics Bureau, 2008).

Compared to the 42 sectors in the China's provincial IO tables, there are only 29 sectors represented in the energy balance tables. To get the largest resolution, we aggregate IO tables using all the overlapping sectors with energy balance tables to 29 sectors.[4] The energy balance tables for each province of China contain only aggregated energy use data for all 24 secondary industry sectors.

The China Energy Statistical Yearbook also provides detailed energy use data for each secondary industry at the national level. We use these two sources to estimate energy use data for each secondary industry at the provincial level. All the energy data is measured by more detailed types of energy products. Using standard conversion factors for China (National Statistics Bureau, 2008), we aggregate the energy data to six energy product types (Coal, Refined oil and coal products, Crude oil, Natural gas, Fuel gas, Electricity and heat) which are consistent with the energy sectors in provincial IO tables.[5]

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[3] Tibet is not included because of lack of data and its small economic size.

[4] The sector mapping is available on request from the authors.

[5] The precise mapping of energy products in the energy balance tables to energy products in IO tables is available by request from the authors.

Integration of different data sources is accomplished using least-square optimization techniques, and is described in detail in Zhang *et al.* (2012a). We find substantial discrepancies between the provincial- and national-level economic accounts, consistent with the findings by Guan *et al.* (2012). Our estimation routine benchmarks the aggregate of provincial-level accounts to national totals, as national accounting methods are more standardized than provincial accounting methods. We then use the provincial data to describe the shares of economic activity in each province. To integrate physical energy flows from official statistics within the regional SAM accounts, we replace energy-market related entries by imputed energy value (money) flows; these are calculated as the product of physical flows and energy price data supplied by the Energy Research Institute of the National Development and Reform Commission (NDRC).

Following the methodology detailed in Böhringer *et al.* (2011), we calculate embodied energy use for each primary energy type, accounting for indirect energy use associated with non-fossil inputs in addition to direct energy use. For this calculation we define the following multi-region IO model (MRIO). Let produced goods, comprising fossil fuels indexed by f, be indexed by i, and $E^{y}_{f,g,r}$ denote embodied energy f for the joint set of activities—produced goods, final demand, investment, and government demand denoted by g in province r. $E^{m}_{i,r}$ describes embodied energy of imported commodities defined as a weighted average of imported varieties across trade partners. In our integrated economy-energy data set, the following accounting identity holds:

$$\overline{a}_{g,r} = \sum_{i} \overline{b}_{i,g,r} + \sum_{i} \overline{c}_{i,g,r} + \overline{d}_{g,r} \tag{1}$$

where $\overline{a}$, $\overline{b}$, and $\overline{c}$ denote the values of output, domestic intermediate inputs, and imported intermediate inputs, respectively. $\overline{d}$ is the sum of factor and tax payments with which no energy use is associated. The multi-regional IO model relates the E variables to equation 1. Embodied energy use in output is thus given by:

$$E^{y}_{f,g,r}\,\overline{a}_{g,r} = \mathit{Direct\,Energy}_{f,g,r} + \underbrace{\sum_{i} E^{y}_{f,i,r}\,\overline{b}_{i,g,r} + \sum_{i} E^{m}_{f,i,r}\,\overline{c}_{i,g,r}}_{Indirect\,Energy}\ . \tag{2}$$

Equation 2 can be represented as a square system of equations which we solve recursively using a diagonalization algorithm (Böhringer *et al.*, 2011).

3.2 MRIO Results

Previous studies have analyzed the heterogeneity in patterns of energy use and CO_2 emissions across China's provinces (Wang, 2011; Guo *et al.*, 2012; Liu *et al.*, 2012). Differences in CO_2 intensity across provinces have been related to economic structure and the relative efficiency of production technology (Liu *et al.*, 2012), although a broad range of factors are important. This section investigates the heterogeneity of China's regional energy system by considering two relevant metrics, specifically the coal use intensity across China's provinces and energy intensity of final demand. This data analysis provides a foundation for interpreting model results described later in the paper.

Table 1 summarizes the energy and electricity embodied in total output by province. Embodied energy by type differs substantially across provinces, and reflects the prevailing technologies and structure of the economy in each region. The intensity of coal use in provincial output varies substantially due to differences in economic structure and the intensity of coal use—the highly developed regions of Guangdong, Shanghai, Beijing, and Jiangsu have the lowest intensity of coal use and have diversified, developed economies, while regions where coal is abundant and technology is less developed (Qinghai, Shanxi, Guizhou, Neimenggu, and Ningxia) have a relative high coal use intensity.

Provinces also differ greatly in both the composition and the efficiency of electric power generation. Some provinces have significant room to improve the fossil fuel efficiency of generation through fuel switching, investment in efficiency upgrades, or new construction of low carbon renewable or nuclear generation. The availability and relative cost of these opportunities will determine to a large extent the cost of abatement in the electricity sector of each province. **Figure 1** shows the intensity of fossil energy use embodied in the unit production of the electricity and heat sector in each province. Hubei, Ningxia and Sichuan have large shares of hydroelectric generation that do not show up in the fossil energy total, leading them to appear less energy intensive overall.

Provinces also differ significantly in terms of the total amount of energy embodied in final demand by households, as well as in its intensity, as shown in Figure 2. Final energy refers to the energy embodied in both internally produced goods and net imports that are consumed by household within each province. As **Figure 2** shows, the provinces that consume large amounts of energy are among the least energy intensive. For example, Guangdong has the highest total household energy use but the lowest energy intensity, and Shandong, Zhejiang, and Liaoning exhibit similar patterns. By contrast, Ningxia, Hainan, and Qinghai have among the highest energy intensities of household consumption but the lowest total energy use by households. Thus a policy that disproportionately targets populous provinces with a high level of energy consumption may miss significant (and likely cost-effective) energy saving opportunities.

4. MODEL AND SCENARIOS

We employ the China Regional Energy Model (C-REM), a multi-commodity, multi-regional static numerical general equilibrium model of the world economy with sub-national detail for China's economy (Zhang *et al.*, 2012a). C-REM was jointly developed through a collaboration between the Institute for Energy, Environment, and Economy at Tsinghua University and the MIT Joint Program on the Science and Policy of Global Change. For this study, we aggregate the data set to 30 provinces in China and six world regions (see **Table 2**), and into 26 commodity groups distinguishing six energy goods (coal, natural gas, fuel gas, crude oil, refined oil and electricity) and 13 non-energy commodities (see **Table 3**). The key features of the model are outlined below.

Table 1. Intensity of primary fuel or electricity use embodied in output by province compared to China's average and the world average levels. Units are million tons of coal equivalents per billion USD in 2007.

Province	Location	Coal	Crude oil	Natural Gas	Electricity
Guangdong	South	0.32	0.19	0.04	0.10
Shanghai	East	0.33	0.28	0.06	0.09
Beijing	North	0.36	0.19	0.05	0.10
Jiangsu	East	0.38	0.18	0.03	0.10
Hainan	South	0.40	0.50	0.18	0.13
Fujian	East	0.41	0.17	0.02	0.10
Zhejiang	East	0.48	0.19	0.03	0.13
Shandong	East	0.52	0.21	0.02	0.12
Guangxi	South	0.52	0.16	0.01	0.11
Sichuan	Southwest	0.53	0.13	0.06	0.11
Hunan	Central	0.57	0.19	0.02	0.11
Hubei	Central	0.57	0.22	0.02	0.13
Tianjin	North	0.58	0.31	0.05	0.12
Henan	Central	0.61	0.12	0.03	0.11
Liaoning	Northeast	0.61	0.35	0.03	0.12
Shaanxi	Northwest	0.63	0.30	0.04	0.11
Jiangxi	East	0.64	0.19	0.02	0.12
Chongqing	Southwest	0.65	0.14	0.09	0.12
Anhui	East	0.66	0.17	0.03	0.11
Heilongjiang	Northeast	0.68	0.29	0.05	0.10
Jilin	Northeast	0.75	0.29	0.03	0.13
Xinjiang	Northwest	0.75	0.42	0.13	0.18
Hebei	North	0.76	0.20	0.03	0.13
Yunnan	Southwest	0.78	0.18	0.03	0.12
Gansu	Northwest	0.80	0.45	0.13	0.19
Ningxia	Northwest	0.84	0.24	0.09	0.25
Neimenggu	North	0.98	0.17	0.04	0.14
Guizhou	Southwest	1.13	0.16	0.04	0.16
Shanxi	North	1.35	0.15	0.03	0.20
Qinghai	Northwest	1.67	0.22	0.09	0.28
China–average		0.56	0.21	0.04	0.12
World–average		0.12	0.15	0.06	0.05

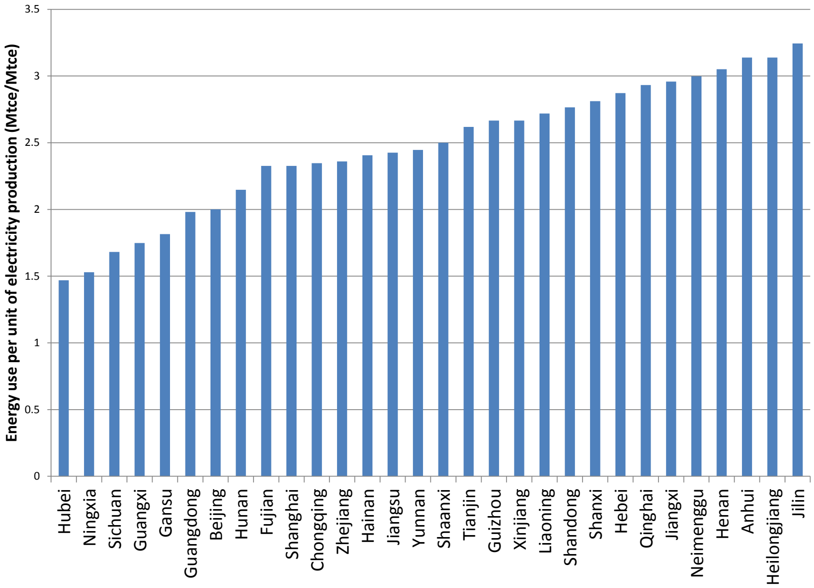

Figure 1. Primary fuel use embodied in the per unit production of electricity and heat, by province (mtce/mtce).

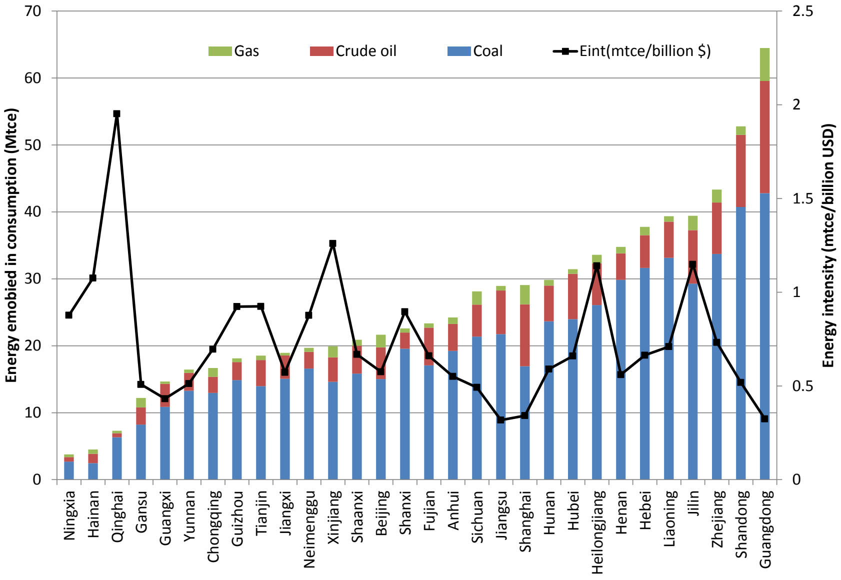

Figure 2. Total and composition of household final energy consumption by fuel type and energy intensity, by province.

Table 2. Regional aggregation in the model.

China's provinces	Other regions
30 provinces*	EUR: Europe (EU 27 + EFTA)
	APD: Asian and Pacific developed countries or regions**
	ASI: Other Asian countries
	NAM: North America (U.S. and Canada)
	CAA: Central Asia, Africa and Former Soviet Union
	ROW: Latin America and rest of the world

* including 4 municipal cities and 5 autonomous regions, and Tibet is not included due to data availability.
** including Japan, Korea, Singapore, Taiwan, Australia and New Zealand.

4.1 Overview of Model Structure

4.1.1 Firm and Household Behavior

For each industry ($i = 1, \ldots, I$, $i = j$) in each region ($r = 1, \ldots, R$) gross output (Y_{ir}) is produced using inputs of labor (L_{ir}), capital (K_{ir}), natural resources including coal, natural gas, crude oil, and land (R_{ir}), and produced intermediate inputs (X_{jir})[6]:

$$Y_{ir} = F_{ir}(L_{ir}, K_{ir}, R_{ir}; X_{1ir}, \ldots, X_{Iir})\,. \tag{3}$$

We employ constant-elasticity-of-substitution (CES) functions to characterize the production technologies. All industries are characterized by constant returns to scale and are traded in perfectly competitive markets. Nesting structures for the production and consumption systems are detailed in Zhang *et al.* (2012a).

Fossil fuels f (coal, crude oil and natural gas) are produced according to a nested CES function combining a fuel-specific resource, capital, labor, and intermediate inputs:

$$Y_{fr} = \left[\alpha_{fr}\, R_{fr}^{\rho_{fr}^{R}} + \nu_{fr}\, \mathit{min}\,(X_{1fr}, \ldots, X_{ifr}, V_{fr})^{\rho_{fr}^{R}}\right]^{1/\rho_{fr}^{R}} \tag{4}$$

where α, ν are share coefficients of the CES function and $\sigma_{fr}^{R} = 1/(1-\rho_{fr}^{R})$ is the elasticity of substitution between the fuel-specific resource and the composite including primary factors, energy and materials. σ_{fr}^{R} is determined by the resource input share and price elasticity of supply η_{fr}. The primary factor and energy composite is a Cobb-Douglas function of the energy input, labor and capital:

$$V_{fr} = L_{fr}^{\beta_1} K_{fr}^{\beta_2} E_{1_{fr}}^{\beta e1} \ldots E_{i_{fr}}^{\beta ei} \tag{5}$$

where β_1, β_2, β_{e1}, …, β_{ei} are shares of the labor, capital and energy inputs. Oil refining, gas production and distribution production are represented in **Figure 3**.

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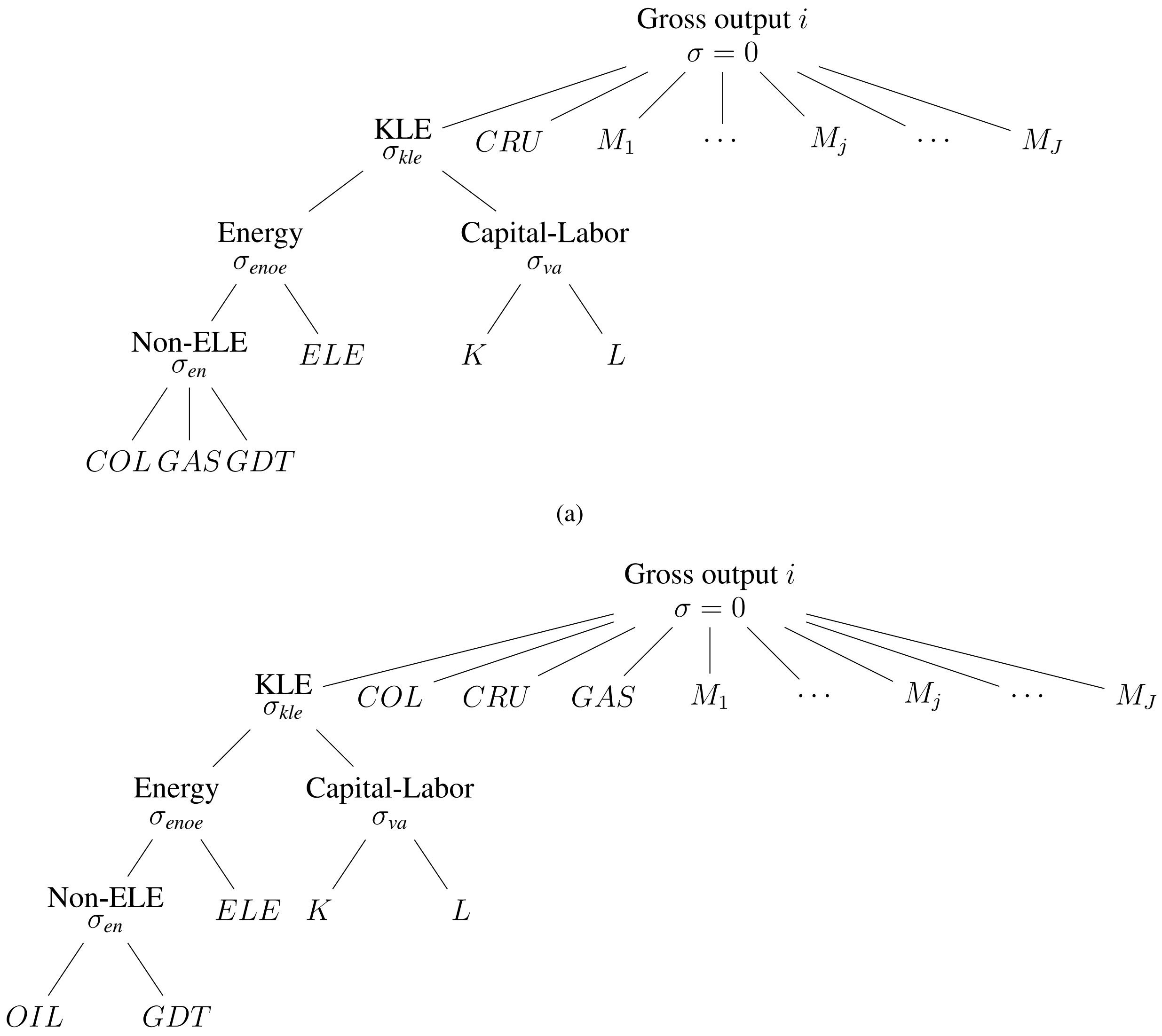
[6] For simplicity, we abstract from the various tax rates that are used in the model. The model includes *ad valorem* output taxes and import tariffs.



(a)

(b)

Figure 3. Structure of production for oil refining $i \in \{\text{OIL}\}$ (a) and gas production and distribution $i \in \{\text{GDT}\}$ (b).

Table 3. Sectoral aggregation in the model.

Sector	Abbreviation	Sectors aggregated from GTAP 8 data set
Agriculture	AGR	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH, CMT, OMT, VOL, MIL, PCR, SGR
Coal	COL	COL
Crude oil	CRU	CRU
Natural gas	GAS	GAS
Minerals mining	OMN	OMN
Light industries	LID	FBT, TEX, WAP, LEA, LUM, PPP
Petroleum, coal products	OIL	OIL
Energy intensive industries	EID	CRP, NMM, I_S, NFM
Transport equipment	TME	MVH, OTN
Other manufacturing industries	OID	FMP, OME, ELE, OMF, CNS
Electricity	ELE	ELY
Gas manufacture and distribution	GDT	GDT
Water	WTR	WTR
Trade	TRD	TRD
Transport	TRP	OTP, WTP, ATP
Other service industry	OTH	CMN, OFI, ISR, OBS, ROS, OSG, DWE

We distinguish several generation technologies, including conventional fossil, hydro, nuclear and wind. In this version of the model, the resource input share is calibrated using the benchmark data. As we lack estimates of price elasticities for supply of nuclear, hydro, and wind in individual provinces in China, we adopt the corresponding elasticities from the MIT Emissions Prediction and Policy Analysis model (Paltsev *et al.*, 2005).

For each sector, the capital mobility feature is represented by following a putty-clay approach. A fraction ϕ of previously-installed capital becomes non-malleable in each sector, and vintaged production in this sector uses this part of capital with fixed shares of all the inputs which are identical to those installed in the base year. The fraction $1-\phi$ of capital is malleable and can be shifted to other sectors in response to input price changes. All the sectors except electricity have the same ϕ value, while ϕ for the electricity sector is higher because capital tends to be less mobile when invested in electricity generation (Sue Wing, 2006).

In each region r, preferences of representative consumers are represented by a Leontief utility function comprised of consumption goods (C_i) and investment (I):

$$U_r = \mathit{min}\left[g(C_{1r},\ldots,C_{Ir}), g(I_{1r},\ldots,I_{Ir})\right] \tag{6}$$

where the function $g(\cdot)$ is a CES composite of all goods. In each region, a single government entity approximates government activities at both central and local levels.

4.1.2 Supplies of Final Goods and Treatment of Domestic and International Trade

All intermediate and final consumption goods are differentiated following the Armington assumption. For each demand class, the total supply of good i is a CES composite of a domestically produced variety and an imported variety, as follows:

$$X_{ir} = \left[\psi^{z}\, ZD_{ir}^{\rho_i^D} + \xi^{z}\, ZM_{ir}^{\rho_i^D}\right]^{1/\rho_i^D} \tag{7}$$

$$C_{ir} = \left[\psi^{c}\, CD_{ir}^{\rho_i^D} + \xi^{c}\, CM_{ir}^{\rho_i^D}\right]^{1/\rho_i^D} \tag{8}$$

$$I_{ir} = \left[\psi^{i}\, ID_{ir}^{\rho_i^D} + \xi^{i}\, IM_{ir}^{\rho_i^D}\right]^{1/\rho_i^D} \tag{9}$$

$$G_{ir} = \left[\psi^{g}\, GD_{ir}^{\rho_i^D} + \xi^{g}\, GM_{ir}^{\rho_i^D}\right]^{1/\rho_i^D} \tag{10}$$

where Z, C, I and G are inter-industry demand, consumer demand, investment demand, and government demand for good i, respectively; and *ZD*, *ZM*, *CD*, *CM*, *ID*, *IM*, *GD*, *GM* are domestic and imported components of each demand class, respectively. The ψ's and ξ's are the CES share coefficients. The Armington substitution elasticities between domestic and imported varieties in these composites are given by $\sigma_i^D = 1/(1-\rho_i^D)$.

The domestic and imported varieties of goods are represented by nested CES functions. We replicate a border effect within our Armington import specification by assuming that goods produced within China are closer substitutes than goods from international sources. We include separate import specifications for China's provinces (indexed by $p = 1, \ldots, P$) and international regions (indexed by $t = 1, \ldots, T$). More detail about the nesting structure of the Armington composites is provided in Zhang *et al.* (2012a).

4.1.3 Equilibrium and Model Solution

Consumption, labor supply and savings result from the decisions of the representative household in each model region that maximize its utility subject to a budget constraint that consumption equals income. Given input prices gross of taxes, firms maximize profits subject to the technology constraints. Firms are assumed to operate in perfectly competitive markets (an assumption that can be relaxed in specific applications) and maximize profit by selling products at a price equal to the marginal cost of production. Numerically, the equilibrium is formulated as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). A model solution must satisfy zero profit and market clearance conditions, with the former condition determining a vector of activity levels and the latter a vector of market-clearing prices. The problem is formulated in GAMS and solved using the mathematical programming system MPSGE (Rutherford, 1999) and the PATH solver (Dirkse and Ferris, 1995) to obtain non-negative prices and quantities.

4.2 Model Scenarios

Given that we are interested in comparing the impacts of policies on a consistent basis, we model all energy cap policies such that they achieve a 20% reduction in China's fossil energy use embodied in final demand of all sectors, households, government and investment activities.[7] In reality the cap is likely to be set several years in advance and allow a fixed increase in coal use relative to a reference year (for instance, the 2015 coal cap allows an increase in coal energy use of 0.4 billion tons relative to 2011).[8] Given our comparative-static model, we choose a 20% reduction as a representative reduction target to compare the impact of alternative designs.

To represent the energy cap in the C-REM model, an endogenous tax is levied on coal or fossil energy use whose level is determined in equilibrium by the constraint on absolute energy consumption. For the national target aimed at limiting fossil energy use at the national level, a nation-wide energy saving allowance trading market is established which allows some provinces to reduce more energy use and sell unused allowances to other provinces. The initial allowance allocation is based on the total final energy consumption for each province.

The objective of a first set of scenarios is to quantify the national and regional changes in the energy mix as well as the associated welfare impacts of constraining energy use through a coal cap relative to a fossil energy cap. These scenarios are defined as follows:

- COAL_CAP: Achieves a 20% reduction in final fossil energy use at the national level by capping coal in primary energy use and implementing the cap through provincial targets (with no coal saving allowance trading market).
- FOSSIL_CAP: Achieves a 20% reduction in final fossil energy use at the national level by capping all final fossil energy use and allowing energy saving allowance trading across provinces.
- CO2_CAP: Achieves the same national reduction in carbon emissions as FOSSIL_CAP by capping carbon emissions and allowing emissions allowance trading across provinces.

The coal cap as modeled here (targeted at primary energy at the provincial level, no inter-provincial trading) is based on current designs under discussion. For an initial comparison with a fossil energy cap, we target a similar energy reduction at the national level through a cap on all forms of fossil energy use (coal, natural gas, and oil) and include an energy saving allowance trading market, before later exploring alternative policy designs that allow less abatement flexibility. Given that the objective of the energy cap is in part to address carbon emissions, we then compare the fossil energy cap to a cap on carbon emissions that achieves a carbon reduction identical to that achieved under the fossil energy cap. By targeting carbon

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[7] A final demand constraint is not directly applied to energy used in intermediate energy production, e.g., electricity generation and coke production.

[8] The coal industry policy for the Twelfth Five-Year Plan suggests that the target is meant to be approximate, with "more or less" (*zuoyou* in Chinese) after the 3.9 billion ton target.

emissions directly the carbon policy would be expected to achieve emissions reductions at least cost by discriminating among energy sources on the basis of carbon content.

To allow for a comparison among alternative fossil energy cap designs, we consider variants of a fossil energy cap with more limited abatement flexibility—either by assigning targets at the regional level, targeting reductions through primary energy only, or both. We therefore consider an additional set of scenarios:

- NCAP_FINALDEMAND: Same as FOSSIL_CAP above, achieves a 20% reduction in final fossil energy use at the national level by capping all final fossil energy use and allowing energy saving allowance trading across provinces.
- NCAP_PRIMDEMAND: Achieves a 20% reduction in final fossil energy use at the national level by capping all primary fossil energy use and allowing energy saving allowance trading across provinces.
- RCAP_FINALDEMAND: Achieves a 20% reduction in final fossil energy use at the provincial level by capping all final fossil energy use with no trading across provinces.
- RCAP_PRIMDEMAND: Achieves a 20% reduction in final fossil energy use at the provincial level by capping all primary fossil energy use with no trading across provinces.

5. RESULTS

To investigate the national and regional impacts of the coal and fossil energy cap policies, we consider the changes in the energy mix and total final fossil energy use as well as the regional distribution of impacts. Coal and fossil energy cap designs are first compared to each other, and then the fossil energy cap is compared to a national cap on energy-embodied CO_2 emissions. We then consider alternative designs for the fossil energy cap, such as a provincial-level implementation (without an allowance market) and imposing the target on primary rather than final energy use. The alternative design choices may improve the ease of policy implementation. We then quantify any associated cost penalty.

5.1 National Impacts

Comparing the impact of a coal cap and a fossil energy cap imposed at the national level, we find that a coal cap that reduces fossil energy use by 20% has the direct effect of reducing coal use by 31%. A coal cap also indirectly causes a reduction of other fossil energy types because higher coal prices increase the cost of final goods, reducing overall demand. Under a coal cap, demand for refined oil and coke products and natural gas falls by about 5%. A fossil energy cap also reduces coal use, but by only 26%, while natural gas demand falls by 19% and refined oil and coke products by around 8%. The modest reduction in oil use reflects its high marginal cost of abatement, given that there are few substitutes for oil in the parts of the economy where it is primarily used, such as the transportation sector.

We compare the results of the fossil energy cap policy to a constraint on carbon embodied in energy use that achieves an identical reduction in emissions, and find that reductions differ only slightly. Coal is reduced by 27%, while gas falls by 14% and refined oil and coke products by 7%. The difference in the contribution of each energy type reflects the fact that coal has a higher carbon content than oil or natural gas, and thus under a policy that targets carbon rather than energy, it is cost effective to further reduce coal. However, it is interesting that the fossil energy cap—a more blunt instrument—produces an outcome that is close to the carbon policy. Our model results suggest that, of all the energy sources, coal can be reduced most cost effectively, whether it is on a carbon or an energy basis.

Turning to the welfare impacts, we find that, at the national level, the coal cap causes the largest loss in welfare, measured as equivalent variation (EV) relative to reference, at (3.2%), while both the fossil energy cap and the carbon policy produce a loss in EV of only 1.3%. The largest welfare loss occurs under the coal cap because it requires that all reductions come from coal use reduction and ignores opportunities to cost effectively reduce energy by constraining other fossil sources. This same logic holds true for carbon reduction, although it should be noted that a coal cap achieves a larger carbon reduction than an equivalent fossil energy cap because of coal's proportionally higher carbon content. Nevertheless, even under a CO_2 emissions cap, coal is not the only contributor to carbon reduction—cost-effective opportunities to reduce emissions by curbing use of oil and natural gas also form part of the solution.

5.2 Regional Impacts

We now turn to examine policy impacts at the regional level. The distributional impacts of each policy will reflect the geography of use for each energy source as well as diversity in the marginal abatement cost. **Figure 4** shows final fossil energy use under each of the policy scenarios compared to a no policy reference case. We find that, relative to either a fossil energy cap or carbon policy, the coal cap results in significantly larger reductions in coal use in some relatively affluent provinces (Beijing, Shanghai, Guangdong, Hebei,and Jiangsu). By contrast, Yunnan, Xinjiang, Inner Mongolia, Guizhou and Gansu—all resource-rich, less developed provinces—would reduce coal more under a national fossil energy or carbon target, reflecting an abundance of low cost opportunities in these provinces.

We now consider how changes in energy use across provinces are reflected in welfare changes. **Figure 5** shows the consumption loss under the coal cap, fossil energy cap and carbon cap policies by province. It is perhaps unsurprising that under the coal cap we find large concentrated welfare costs in provinces that face high marginal costs of abatement, either because they have already achieved significant efficiency in using coal (Beijing, Shanghai, Guangdong, Jiangsu and Shandong) or because they have few competitive substitutes for the coal they already use (Beijing and Shandong) or because they are main coal producers (Shanxi and Shaanxi). For instance, Guangdong and Jiangsu have highly developed and relatively modern industrial and electricity sectors that have already realized significant coal use efficiency. In these cases, coal cap will have significant negative impacts on economy and household welfare.

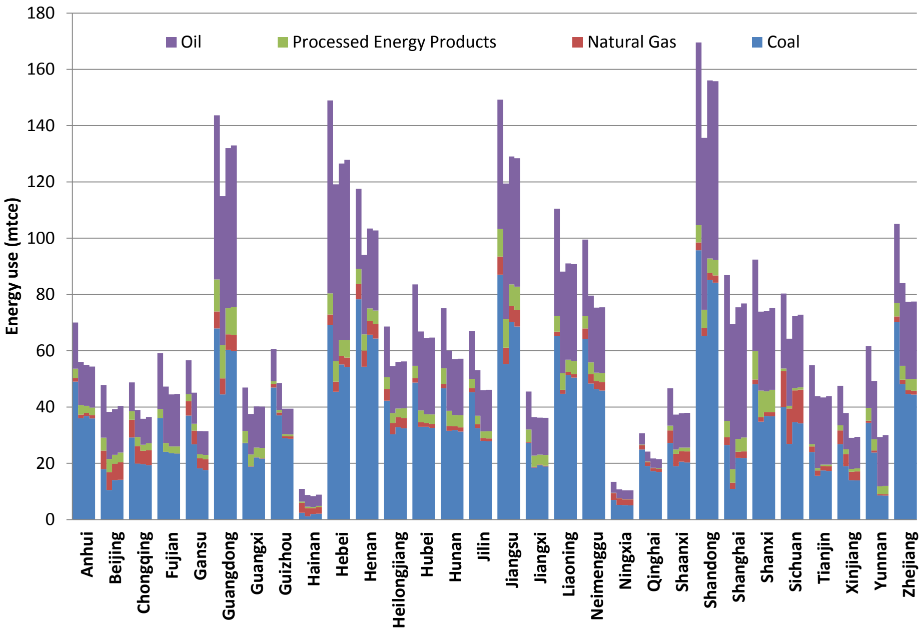

Figure 4. Final fossil energy use under each of the policy scenarios compared to a no policy reference case (from left to right for each province: no policy, COAL_CAP, FOSSIL_CAP and CO2_CAP).

Both the fossil energy cap and the carbon cap result in similar patterns of welfare loss across provinces. This result is not surprising given that the only difference between the two policies is that the carbon cap penalizes embodied carbon rather than energy use alone, and the overall contribution of the various energy types is similar. In many provinces, losses under a fossil energy or carbon cap are less pronounced relative to the losses under the coal cap, as both the fossil energy cap and the carbon cap are designed to allow inter-provincial trading that takes advantage of the large, concentrated availability of abatement opportunities in some provinces. As mentioned above, Gansu, Guizhou, Qinghai and Yunnan all play an important role in reductions under a fossil energy cap or carbon cap (see Figure 4), and thus the welfare effects in these cases are slightly more pronounced (see Figure 5). As the coal cap does not fully take advantage of low cost abatement opportunities in these provinces, they are actually better off under a coal cap—despite the fact that, at the national level, welfare loss is significantly larger. The consumption losses in the coal-rich provinces Shanxi and Shaanxi are the most insensitive to the choice of policy, reflecting the fact that the provincial coal cap target is similar to the cost-effective provincial contribution that results under a national fossil energy cap.

5.3 Policy Design Choices Under an Energy Cap

We now consider how changing the implementation of a fossil energy cap affects both the energy mix composition and welfare outcomes at the national and regional levels. Specifically, applying targets at the regional level may be politically attractive in China, given that economic and other goals (environmental, health, public safety) are evaluated at the provincial level.

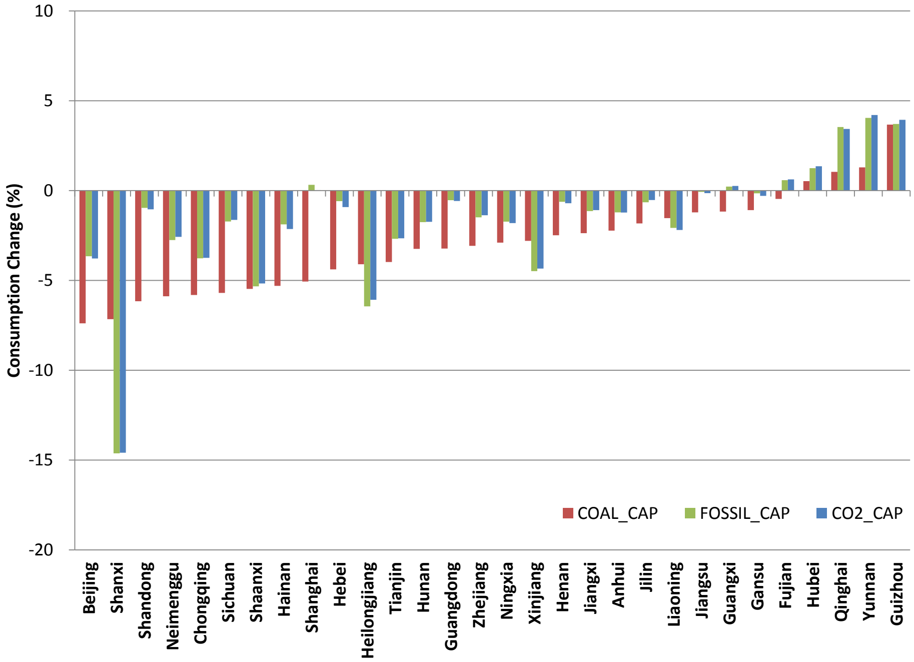

Figure 5. Consumption change in percent under the COAL_CAP, FOSSIL_CAP and CO2_CAP scenarios.

Developing a trading mechanism would require the development of new institutions to allow the verification and payment for abatement undertaken outside of provincial borders. It may also prove more feasible to cap primary, rather than final, energy consumption, given that primary energy use is easier to track. The purpose of this exercise is to quantify the welfare impact of moving to alternative policy configurations in order to make explicit the tradeoffs inherent in choices facing policymakers.

5.3.1 National versus regional targets

Regional targets spread the burden of reducing fossil energy use equally across provinces, but with the result that abatement is undertaken at different marginal costs, raising the overall cost of the policy. At the national level, the welfare penalty for moving from a national to a regional (provincial) fossil energy cap is a 26% increase in the welfare loss to -1.6%. Provinces with relatively high marginal abatement costs contribute more than would be expected under regional targets. **Figure 6** shows how this welfare impact is distributed across provinces. Most provinces incur higher welfare costs (particularly in Beijing, Tianjin, Shanxi, Shandong and Xinjiang). In general moving from national to regional targets does not alter the direction of the welfare effects by province. The corresponding impact on the primary energy mix is shown in **Figure 7**.

5.3.2 Primary versus final energy use

Capping final energy instead of primary energy has more pronounced effects on welfare, particularly when combined with regional targets. At the national level, targeting primary energy at the national level increases the welfare loss by 34% relative to a national policy that targets

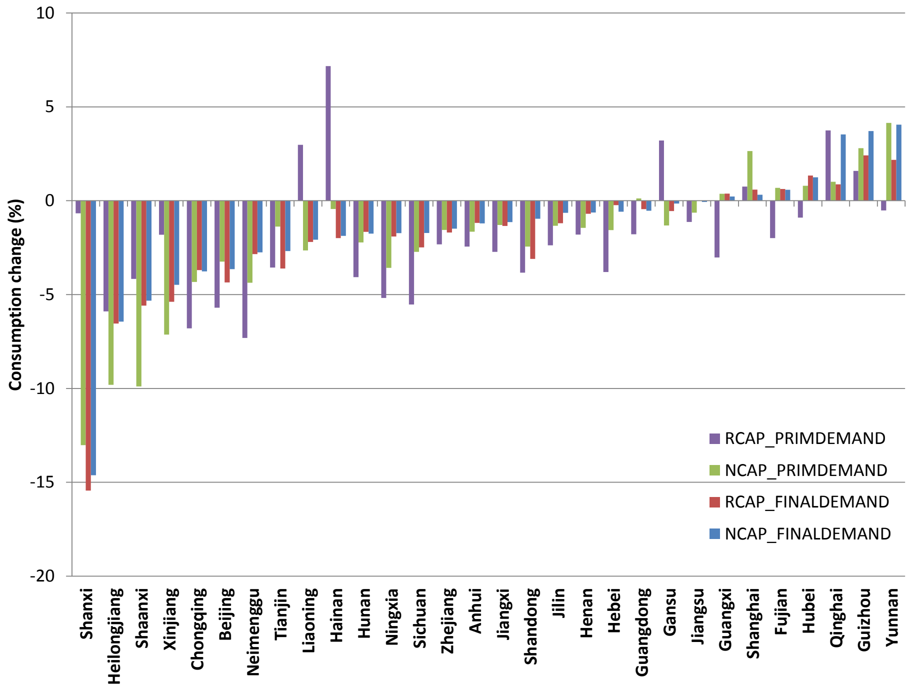

Figure 6. Relatuve consumption change in percent under the three variants of the Fossil Energy Cap policy compared to NCAP_FINALDEMAND.

final demand; if the policy is implemented at the regional level, the incremental welfare loss increases by 84%. The regional distribution of impacts changes dramatically as well (Figure 6). A regional policy that caps primary fossil energy changes the direction of welfare effects in Shanxi, Liaoning and Yunnan, in some cases by very large magnitudes. These differences likely reflect the distinct geographies associated with primary fossil energy use and fossil energy used in final demand. Where abatement opportunities and costs within a single province differ widely between primary and final energy demand, the choice of target can have large effects on welfare.[9]

5.4 Impact on Non-Fossil Energy

As mentioned previously an energy cap would not be applied on non-fossil energy sources, including electricity generation from nuclear, hydro and wind resources. However an energy cap could affect the use of these sources if these non-fossil sources prove to be cost-effective substitutes for coal or fossil energy types. Indeed, we find that all policies considered result in an increase in non-fossil energy use in every province. Shanghai, Shandong and Jiangsu in particular see strong increases in non-fossil energy use under the regional or coal caps, relative to the

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[9] We further performed a sensitivity analysis to consider the impact of changing target stringency on the relative cost effectiveness of the policy designs considered. Compared to a base case reduction of 20%, increasing the target stringency to 30% or reducing it to 10% did not affect the cost-effectiveness ranking of policy designs. However, we do note that, as target stringency increases, targeting primary rather than final energy leads to a larger incremental welfare decrease, especially in the regional policy scenarios.

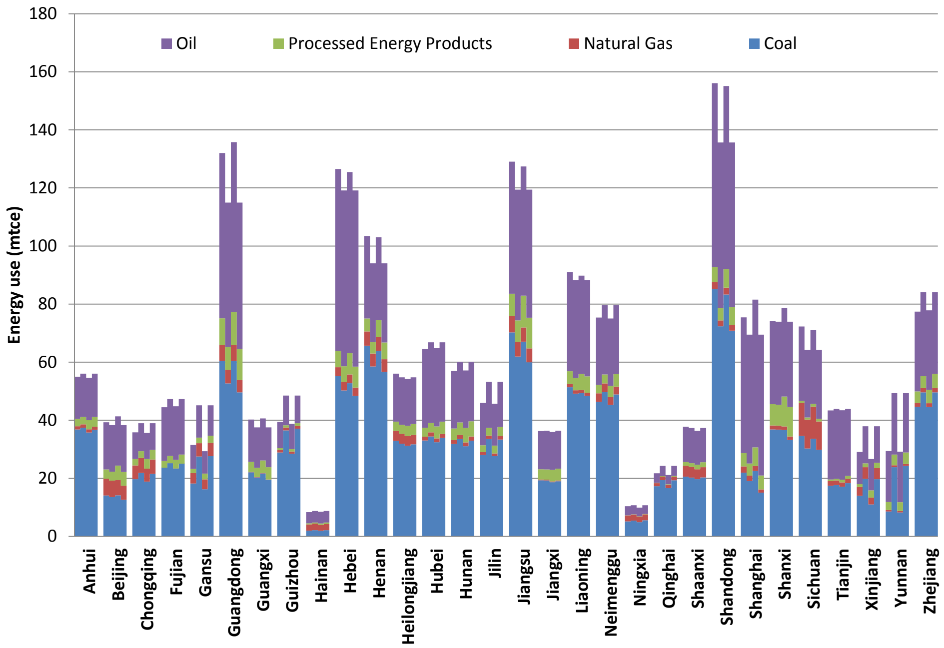

Figure 7. Final fossil energy use under the four variants of the Fossil Energy Cap policy (from left to right for each province: NCAP_FINALDEMAND, RCAP_FINALDEMAND, NCAP_PRIMDEMAND and RCAP_PRIMDEMAND).

national policies or carbon cap.[10]

6. CONCLUSIONS

If the objective of policy is to reduce fossil energy use, we find that a coal cap as currently proposed (e.g., on primary energy demand at the regional level and without energy-saving allowance trading) is less cost effective than a fossil energy cap. This conclusion is robust to a comparison with all variants of a fossil energy cap modeled in this analysis.[11] A fossil energy cap that achieves an equivalent reduction in energy is more cost effective than a coal cap because it allows cost-effective reductions to be achieved through abatement of other carbon-intensive energy sources. If the objective is to reduce CO_2 emissions, we find that a national fossil energy cap that targets energy in final demand is almost as efficient as a CO_2 emissions cap. This is because coal is a major source of low cost reductions in both energy and emissions, and contributes significantly (but not exclusively) to reductions under both policies. Excluding

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[10] One caveat is that non-fossil electricity generation technology is not represented as backstop technologies in the model. Because of the constant elasticity of substitution (CES) function representation of technology, this implies that if there is no nuclear, hydro and wind electricity generation in the reference scenario, i.e. an initial share of zero in the CES function, there will be no new installation in the policy scenarios. The representation of advanced non-fossil electricity generation options in the model is beyond the scope of this paper.

[11] For all cases, we assume that the costs of compliance with policy are passed through to final users. However, China has managed electricity pricing (Lam, 2004), and so some end use decisions would not respond to the policy, reducing overall cost effectiveness.

carbon-intensive primary fuels, such as natural gas and oil, from an energy cap indirectly subsidizes these fuels, which could in turn offset the climate benefits associated with capping coal alone.

This finding may not be intuitive to those who point out that a fossil energy cap would indirectly penalize low carbon fuels, such as natural gas, which it is argued would be phased out first due to their high costs of production. Our model results emphasize that it is essential not to conflate cost of production with marginal abatement cost, the latter of which determines where reductions in fuel use can be undertaken most cost effectively. Indeed, we find that natural gas is reduced only slightly more under a fossil energy cap relative to a carbon cap, and the opposite is found for coal, which is reduced slightly less. As coal is inexpensive, the shadow price on energy (or carbon) causes a large increase in the price of coal in percentage terms; natural gas, which is already relatively costly, increases in price by a smaller relative percentage. Regardless of whether energy or CO_2 is the target, reducing coal use proves to be a dominant abatement strategy. The distributional impacts of both policies are also qualitatively and quantitatively similar.

Regardless of cost effectiveness, in practice policies that build on existing institutions and practices may stand a greater chance of implementation. A coal cap may be easier to implement because it focuses on a single commodity, and has perhaps the strongest policy precedent in China. However, as our analysis indicates, a similar amount of energy can be reduced through a national fossil energy cap at only 40% of the cost of a coal-only cap.[12] When it comes to the design of a fossil energy cap, a national constraint on fossil energy embodied in final demand (with an energy-saving allowance trading system) is the most cost effective. Assigning targets at the regional level and/or on primary energy use carries an incremental welfare penalty of 27% to 84%, relative to a policy that assigns a national constraint that targets final energy demand. Despite these welfare penalties, alternative policy designs may prove more politically feasible. Policy targets in China have traditionally been implemented through regional channels, with enforcement delegated to provincial governments. We find that moving from national to regional fossil energy targets carries a modest welfare penalty and does not substantially change the distribution of impacts relative to the national target. The welfare penalty is larger when moving to a target on primary energy, particularly if it is implemented at the regional level. The welfare penalties associated with alternative policy designs should be explicitly considered in the policy process.

While a fossil energy cap may be a reasonable substitute for a direct constraint on carbon in the target range we consider here, it would not address another major concern of China's policymakers—energy security threats associated with reliance on imported oil. Neither a fossil energy cap nor a carbon cap would lead to significant reduction in petroleum demand, given the lack of substitutes for its use in transportation and chemical production. If energy security is the

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[12] The magnitude of this advantage depends on the design of the coal and fossil energy cap. We also model a national cap on coal (not shown) and find that it results in a lower welfare loss of 2.7%. This loss is still greater than the loss expected under the least cost effective of the fossil energy cap designs modeled, a regional cap that acts by constraining primary fossil energy, which has a welfare loss of -2.3%.

desired objective, complementary policies will be needed—for instance, a tax or cap on petroleum use as well as incentives to develop alternatives to petroleum-intensive activities. This analysis underscores that a sharp policy instrument is always preferred to a blunt instrument, but that some blunt instruments are sharper than others.

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7. REFERENCES

21^{st} Century Business Herald, 2011: Nine regions have set initial coal consumption caps.

Böhringer, C., J. C. Carbone and T. F. Rutherford, 2011: Embodied Carbon Tariffs.

Bushnell, E. T., James B.and Mansur, 2011: Vertical targeting and leakage in carbon policy. *The American Economic Review*, **101**(3): 263–267.

Cao, J., M. S. Ho and D. W. Jorgenson, 2009: The local and global benefits of green tax policies in China. *Review of Environmental Economics and Policy*, **3**: 189–208.

Cong, R.-G. and Y.-M. Wei, 2010: Potential impact of (CET) carbon emissions trading on China's power sector: A perspective from different allowance allocation options. *Energy*, **35**(9): 3921–3931.

Dai, H., T. Masui, Y. Matsuoka and S. Fujimori, 2011: Assessment of China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. *Energy Policy*, **39**(5): 2875–2887.

Dirkse, S. P. and M. C. Ferris, 1995: The PATH Solver: a non-monontone stabilization scheme for Mixed Complementarity Problems. *Optimization Methods and Software*, **5**: 123–156.

GTAP, 2012: *Global Trade, Assistance, and Production: The GTAP 8 data base*. Center for Global Trade Analysis, Purdue University.

Guan, D., Z. Liu, Y. Geng, S. Lindner and K. Hubacek, 2012: The gigatonne gap in China's carbon dioxide inventories. *Nature Climate Change*, **2**: 672–674.

Guo, J., Z. Zhang and L. Meng, 2012: China's provincial CO_2 emissions embodied in international and interprovincial trade. *Energy Policy*, **42**: 486–497.

He, Y. X., S. L. Zhang, L. Y. Yang, Y. J. Wang and J. Wang, 2010: Economic analysis of coal price - electricity price adjustment in China based on the CGE model. *Energy Policy*, **38**(11): 6629–6637.

Kraemer, S., 2012: China to Simply Cap Coal Use Within 3 Years. *Scientific American*, **March 9**.

Lam, P.-L., 2004: Pricing of electricity in China. *Energy*, **29**: 287–300.

Lan, L., 2012: Energy use may be capped for 2015. People's Daily Online.

Li, N., M.-j. Shi and F. Wang, 2009: Roles of regional differences and linkages on Chinese regional policy effect in CGE analysis. *Systems Engineering - Theory and Practice*, **29**: 35–44.

Liu, Z., Y. Geng, S. Lindner and D. Guan, 2012: Uncovering China's greenhouse gas emission from regional and sectoral perspectives. *Energy*, **45**(1): 1059–1068.

Lu, C., Q. Tong and X. Liu, 2010: The impacts of carbon tax and complementary policies on Chinese economy. *Energy Policy*, **38**: 7278–7285.

Mathiesen, L., 1985: Computation of economic equilibria by a sequence of linear complementarity problems. *Mathematical Programming Study*, **23**: 144–162.

Matus, K., K.-M. Na, N. E. Selin, L. N. Lamsal, J. M. Reilly and S. Paltsev, 2012: Health damages from air pollution in China. *Global Environmental Change*, **22**: 5566.

National Statistics Bureau, 2008: 2007 China Energy Statistical Yearbook.

National Statistics Bureau, 2011a: 2007 China Regional Input-Output Tables.

National Statistics Bureau, 2011b: 2010 China Statistical Yearbook.

NDRC, 2012: Twelfth Five-Year Plan Coal Industry Development Plan (In Chinese).

Paltsev, S., J. Reilly, H. Jacoby, R. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian and M. Babiker, 2005: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MIT JPSPGC *Report 125*, August, 72 p. (http://mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf).

People's Daily Online, 2011: Wu Yin: China's coal consumption in 2015 should be controlled within 3.9 billion ton.

Point Carbon, 2012: China's Tianjin sets 2015 coal consumption cap. *Point Carbon - Reuters*.

Reuters, 2012: China may miss new target to cut coal output growth.

Rutherford, T. F., 1995: Extension of GAMS for complementarity problems arising in applied economics. *Journal of Economic Dynamics and Control*, **19**(8): 1299–1324.

Rutherford, T. F., 1999: Applied general equilibrium modeling with MPSGE as a GAMS subsystem: an overview of the modeling framework and syntax. *Computational Economics*, **14**: 1–46.

Sue Wing, 2006: The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO_2 emissions. *Energy Policy*, **34**: 3847–3869.

Wang, X., 2011: On China's energy intensity statistics: Toward a comprehensive and transparent indicator. *Energy Policy*, **39**(11): 7284–7289.

Wei, C., J. Ni and L. Du, 2012: Regional allocation of carbon dioxide abatement in China. *China Economic Review*, **23**(3): 552–565.

Xinhua Press, 2011: Shandong Province will cap coal consumption during the Twelfth Five-Year Plan.

Zhang, D., S. Rausch, V. Karplus and X. Zhang, 2012a: Quantifying regional economic impacts of CO_2 intensity targets in China. MIT JPSPGC *Report 230*, September, 26 p. (http://globalchange.mit.edu/files/document/MITJPSPG_Rpt230.pdf).

Zhang, F., Y. Guo and X. Chen, 2011: Research on China's power sector carbon emissions trading mechanism. *Energy Procedia*, **12**(0): 127–132.

Zhang, Q., K. He and H. Huo, 2012b: Cleaning China's air. *Nature*, **484**: 161–162.

Zhang, Z., 1998: Macroeconomic effects of CO_2 emission limits: A computable general equilibrium analysis for China. *Journal of Policy Modeling*, **20**(2): 213–250.

Zhang, Z., 2000: Can China afford to commit itself an emissions cap? An economic and political analysis. *Energy Economics*, **22**: 587–614.

Zhao, X. and L. Ortolano, 2010: Implementing China's national energy conservation policies at state-owned electric power generation plants. *Energy Policy*, **38**(10): 6293–6306.

Zhou, J., M. Duan and C. Liu, 2011: Output-based allowance allocations under China's carbon intensity target. *Energy Procedia*, **5**(0): 1904–1909.

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