The energy and CO_2 emissions impact of renewable energy development in China*

Tianyu Qi, Xiliang Zhang and Valerie Karplus

*Reprinted from
Energy Policy, 68 (May 2014): 60–69 (doi:10.1016/j.enpol.2013.12.035)

Reprint 2014-9

The MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Program brings together an interdisciplinary group from two established MIT research centers: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the Program's work lies MIT's Integrated Global System Model. Through this integrated model, the Program seeks to: discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is one of a series intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

Ronald G. Prinn and John M. Reilly,
Program Co-Directors

For more information, contact the Program office:
MIT Joint Program on the Science and Policy of Global Change

Postal Address:
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)

Location:
Building E19, Room 411
400 Main Street, Cambridge

Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: ***globalchange@mit.edu***
Website: ***http://globalchange.mit.edu/***

Energy Policy 68 (2014) 60–69

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

The energy and CO_2 emissions impact of renewable energy development in China

Tianyu Qi [a], Xiliang Zhang [a,*], Valerie J. Karplus [b]

[a] Institute of Energy, Environment and Economy, Tsinghua University, Sino-Italian Energy and Environment Building, Room 325, Beijing 100084, China
[b] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room E19-429ha, Cambridge, MA, 02139, USA

HIGHLIGHTS

- The 2020 targets and subsidies make renewable electricity economically viable in the short term.
- Cumulative CO_2 emissions (2010-2020) are reduced by 1.8% in the Current Policy scenario.
- Displacing fossil fuels from electricity leads to increases in other sectors, offsetting emissions reductions.
- The expansion of renewables after 2020 depends on cost reductions achieved.

ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form
6 November 2013
Accepted 13 December 2013
Available online 7 February 2014

Keywords:
China
Renewable energy
CO_2 emissions
CGE modeling

ABSTRACT

China has adopted targets for developing renewable electricity that would require expansion on an unprecedented scale. During the period from 2010 to 2020, we find that current renewable electricity targets result in significant additional renewable energy installation and a reduction in cumulative CO_2 emissions of 1.8% relative to a No Policy baseline. After 2020, the role of renewables is sensitive to both economic growth and technology cost assumptions. Importantly, we find that the CO_2 emissions reductions due to increased renewables are offset in each year by emissions increases in non-covered sectors through 2050. We consider sensitivity to renewable electricity cost after 2020 and find that if cost falls due to policy or other reasons, renewable electricity share increases and results in slightly higher economic growth through 2050. However, regardless of the cost assumption, projected CO_2 emissions reductions are very modest under a policy that only targets the supply side in the electricity sector. A policy approach that covers all sectors and allows flexibility to reduce CO_2 at lowest cost – such as an emissions trading system – will prevent this emissions leakage and ensure targeted reductions in CO_2 emissions are achieved over the long term.

1. Introduction

China has adopted targets for the deployment of renewable energy through 2020. These targets are sizable both in terms of total installed capacity as well as the anticipated contribution of renewable energy to total electricity generation.[1] An important objective of renewable energy development in China is to reduce CO_2 emissions and reliance on imported energy by decoupling rising fossil energy use from economic growth over the next several decades. This decoupling is also expected to have a positive impact on local air and water quality. The cost of environmental pollution was estimated to exceed 4% of the country's GDP between 1995 and 2003 (The World Bank and China Ministry of Environmental Protection, 2007; Matus et al., 2012). Emphasis on renewable energy is also designed to promote China's competitiveness as a leading global supplier of clean, low cost renewable energy technologies (Paltsev et al., 2012). In this paper, we quantify the impact of China's renewable energy targets on both renewable and fossil energy use as well as the impact on CO_2 emissions, both of which are of significant interest to policymakers in China and abroad.

Targets for renewable energy deployment form part of a broader set of energy and climate policies that China's central government has defined for the period through 2020. National goals have been set for energy and carbon intensity[2] reduction, as well as for the contribution from non-fossil sources to total

* Corresponding author. Tel.: +8610 62792866.
E-mail address: zhang_xl@tsinghua.edu.cn (X. Zhang).

[1] Targets for installed capacity have been specified for all renewable generation types, while generation targets have only been set for wind (390 TWh in 2020).

[2] Carbon intensity is defined as the ratio of carbon dioxide emissions per unit of output. As a measure of output we use real gross domestic product (GDP).

0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.12.035

primary energy. These broad goals are then supported by measures that target increases in specific types of generation—targets applied to wind, solar, and biomass electricity generation are the focus of this analysis. As officials begin considering policies for the period beyond 2020, there is a strong need to understand how such supply-side targets for renewable energy could contribute to China's broader energy and climate policy goals. In order to understand what role renewable energy could play in achieving low carbon development, we assess the impact of current renewable energy targets.

This analysis is organized as follows. First, we discuss in detail recent developments in China's energy and climate policy, the expected contribution of renewable energy and related policies, and the status of renewable energy development in China. Second, we describe the model used in this analysis, the China-in-Global Energy Model or C-GEM. We include a detailed discussion of how renewable energy is represented in this model. Third, we describe the policy scenarios and how they are implemented in the modeling framework. Fourth, we present the modeling results, which explore the impacts of China's renewable energy targets on primary energy use, CO_2 emissions, and consumption under alternative economic growth and technology cost assumptions. Fifth, we discuss the relationship between China's renewable energy targets and the nation's long-term energy and climate policy goals.

2. Renewable energy policy in China

2.1. Energy and climate policy goals in China

China's energy and climate policy sets forth a national carbon intensity reduction target of 17% as part of the Twelfth Five-Year Plan (FYP) (2010–2015). This target is consistent with the nation's commitment at the Copenhagen climate talks of achieving a 40–45% CO_2 intensity reduction by 2020, relative to a 2005 baseline. The Twelfth Five-Year Plan includes for the first time a CO_2 intensity target in contrast to previous Five-Year Plans, which defined only energy intensity targets (Yuan et al., 2012). Looking ahead, reducing CO_2 emissions remains an important energy-related policy goal alongside energy security, air quality improvement, and balancing economic development across rural-urban and east-west dimensions.

Alongside carbon and energy intensity goals, China also aims to increase the contribution of non-fossil energy (including renewable sources and nuclear) to total primary energy use. In 2010, the actual non-fossil energy share reached 9.1%. Looking ahead, non-fossil energy share targets increase to 11.4% in 2015 and 15% in 2020. The non-fossil energy target is viewed as way to reinforce the goal of carbon reduction specifically through the deployment of low-carbon energy (and especially electricity) sources. While the non-fossil energy target focuses on expanding the contribution of technology to CO_2 emissions reduction, broad mandates for improving industrial and building energy efficiency have also been strengthened and expanded during the Eleventh and Twelfth Five-Year Plans (Institute for Industrial Productivity, 2012; Qi et al., 2012).

2.2. Renewable energy deployment targets

The expansion of China's renewable energy development in recent years has been substantial. China's renewable energy supply from wind, solar, and non-traditional biomass (a category including biomass for electricity, biogas, and biofuels) increased threefold between 2000 and 2010, from 95 million tons of coal equivalent (Mtce) to 293 Mtce (Zhao et al., 2012). The composition of renewable energy in China in 2010 is shown in Fig. 1. To achieve the target of increasing the national share of non-fossil energy to 15% in 2020, the central government has set new targets in its Twelfth FYP for nuclear and renewable energy deployment in China 2015 and has suggested targets for 2020, as shown in Table 1.

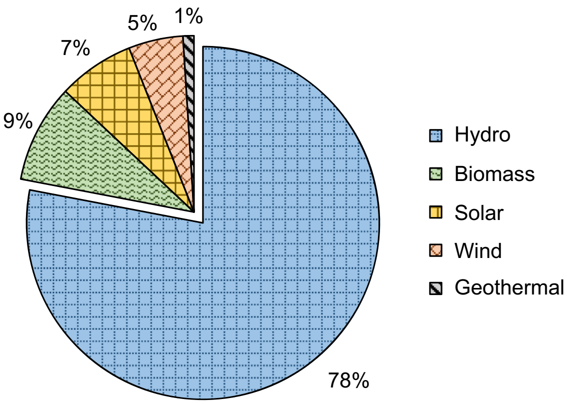

Fig. 1. Composition of renewable energy in China in 2010 (excludes traditional biomass).

Table 1
Published targets for installed capacity in 2015(State Council of China, 2013) and 2020 (China electricity council, 2012).

Renewable energy targets	**Installed capacity (GW)**		
Year	**2010**	**2015**	**2020**
Nuclear	10.8	40	58
Hydro	213	290	420
Wind	31	100	200
Solar	0.8	35	50
Biomass	5.5	13	30

The new targets foresee a six-fold increase in wind power, a 62.5-fold increase in solar power, and a 5.4-fold increase in biomass electricity by 2020 relative to 2010 (for wind, some expect this deployment to occur even faster). Rather than simply increasing installed capacity as before, the new plan also emphasizes the objectives of energy efficiency, technological improvements and large-scale transmission infrastructure, which are expected to effectively improve capacity utilization. Moreover, the new plan is expected to strengthen demand for domestically-produced components, insulating this traditionally export-oriented industry from changing regulatory and market conditions abroad (Santalco, 2012).

While the current targets may seem ambitious, the government has committed significant resources to innovation and diffusion in renewable energy over the long term. The central government has played a key role in many aspects of organizing and funding R&D, as well as supporting investment in and commercialization of renewable technologies. In 2010, a total amount of $43.6 billion in low interest loans and grants was provided by the China Development Bank, with government backing, to support China's renewable industry (China Greentech Initiative, 2011; Santalco, 2012). The central government also introduced policies to accelerate renewable deployment in recent years. Feed-in-tariffs (FITs) were established for wind electricity in 2009, ranging from RMB 0.51 to 0.61 per kWh (US$ 0.08–0.09/kWh). A recent empirical study focusing on the combined effect of measures including public R&D support, concessions, feed-in tariff, power surcharge for renewable electricity and tax relief in China has greatly stimulated the growth of China's wind and solar PV industry

Table 2
Sectors and regions in the China-in-Global Energy Model (C-GEM).

Sector	Description	Region	Description
Crops	Food and non-food crops produced on managed cropland	China (CHN)	Mainland China
Forest	Managed forest land, logging activities	United States (USA)	United States of America
Livestock	Animal husbandry and animal products	Canada (CAN)	Canada
Coal	Mining and agglomeration of hard coal, lignite and peat	Japan (JPN)	Japan
Oil	Extraction of petroleum	South Korea (KOR)	South Korea
Gas	Extraction of natural gas	Developed Asia (DEA)	Hong Kong, Taiwan, Singapore
Petroleum	Refined oil and petroleum products	Europe Union (EUR)	Includes EU-27 plus countries in the European Free Trade Area (Switzerland, Norway, Iceland)
Electricity	Electricity production, transmission and distribution	Australia–New Zealand (ANZ)	Australia, New Zealand, and other territories (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories)
Non-metallic minerals products	Cement, plaster, lime, gravel, concrete	India (IND)	India
Iron and steel	Manufacture and casting of iron and steel	Developing South-East Asia (SEA)	Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia, Laos, Southeast Asian countries not elsewhere classified
Non-ferrous metals products	Production and casting of copper, aluminum, zinc, lead, gold, and silver	Rest of Asia (ROA)	Asian countries not elsewhere classified
Chemical rubber products	Basic chemicals, other chemical products, rubber and plastics	Mexico (MEX)	Mexico
Fabricated metal products	Sheet metal products (except machinery and equipment)	Middle East (MES)	Iran, United Arab Emirates, Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia
Food and tobacco	Manufacture of foods and tobacco	South Africa (ZAF)	South Africa
Equipment	Electronic equipment, other machinery and equipment	Rest of Africa (AFR)	African countries not elsewhere classified
Other industries	Other industries	Russia (RUS)	Russia
Mining	Mining of metal ores, uranium, gems, other mining and quarrying	Rest of Europe (ROE)	Albania, Croatia, Belarus, Ukraine, Armenia, Azerbaijan, Georgia, Turkey, Kazakhstan, Kyrgyzstan, European countries not elsewhere classified
Construction	Building houses factories offices and roads	Brazil (BRA)	Brazil
Transportation services	Water, air and land passenger and freight transport, pipeline transport	Latin America (LAM)	Latin American countries not elsewhere classified
Other services	Communication, finance, public services, dwellings and other services		

(Wang et al., 2012; Renewable Energy World, 2005; Qi et al., 2012; Liu et al., 2011, 2013; Huo et al., 2011). These support mechanisms have underpinned the expansion of China's renewable energy so far, and are likely to enable achievement of the 2020 targets.

3. Model description

This paper employs the China-in-Global Energy Model (C-GEM) to evaluate the energy and CO_2 emissions impacts of China's renewable energy development. The C-GEM is a multi-regional, multi-sector, recursive-dynamic computable general equilibrium (CGE) model of the global economy that separately represents 19 regions and 20 sectors as shown in Table 2 below. In the model, China is represented as a single region.

Energy production and consumption are explicitly represented in each sector, capturing its change over time and policy impacts. In each region r, the representative producer in sector i chooses a level of output $y_{r,i}$, values of primary factors $K_{r,fi}$, and an intermediate input $X_{r,fi}$ in order to maximize profit, subject to the characteristics of the production function $\varphi_{r,i}$, which describes the structure of currently available production technologies in sector i. The producer's decision function can be expressed as:

$$\max \pi_{r,i} = p_{r,i} \times y_{r,i} - C_{r,i}(p_{r,j}, w_{r,f}, y_{r,i})$$
$$\text{s.t.} \quad y_{r,i} = \varphi_{r,i}(x_{r,ji}, k_{r,fi}) \tag{1}$$

where $\pi_{r,i}$ is profit, $C_{r,i}$ represents the cost function for sector i in region r, and $p_{r,i}$ and $w_{r,f}$ are the price of good i and factor f, respectively. The constant elasticity of substitution (CES) form is used to model the cost function. The constant return to scale (CRS) assumption of the CES function simplifies the production optimizing problem described in Eq. (1). From the first order condition and Shepard's Lemma, the demand function for intermediate input $X_{r,fi}$ (Eq. (2)) and factor $K_{r,fi}$ demand function (Eq. (3)) for the production sector i are given as follows:

$$x_{r,ji} = y_{r,i}\frac{\partial c_{r,i}}{\partial p_{r,j}} \tag{2}$$

$$k_{r,fi} = y_{r,i}\frac{\partial c_{r,i}}{\partial w_{r,f}} \tag{3}$$

where $c_{r,i}$ is the unit cost function.

Representative agents choose consumption and saving to maximizing their welfare $W_{r,i}$ given their level of income M, which is generated from the rent of factor supply.

$$\max W_{r,i}(d_{r,i}, s_{r,i})$$
$$\text{s.t.} \quad M_{r,i} = p_{r,s}s_r + \sum_i p_{r,i}d_{r,i} \tag{4}$$

where s_r is savings, $d_{r,i}$ is the final demand, and $W_{r,i}$ is a utility function with CES form. Similar to production, consumption demand for goods d and savings s is derived as follows:

$$d_{r,i} = m_r\frac{\partial E_r(p_{r,i}, p_{r,s})}{\partial p_{r,i}} \tag{5}$$

$$s_r = m_r\frac{\partial E_r(p_{r,i}, p_{r,s})}{\partial p_{r,s}} \tag{6}$$

where m_r is the initial consumption level in each region and $E_r(p_{r,i}, p_{r,s})$ is the unit expenditure function given $p_{r,i}$, the price of goods i and $p_{r,s}$, the opportunity cost of saving.

Table 3
Advanced technologies in the C-GEM model.

Technology	Description
Wind	Produces electricity from wind energy
Solar	Produces electricity from solar energy
Biomass electricity	Produces electricity from biomass energy
IGCC	Produces electricity from coal using integrated gasification combined cycle (IGCC) technology
IGCC-CCS	Produces electricity from coal using IGCC technology with carbon capture and storage
NGCC	Produces electricity from natural gas using natural gas combined cycle (NGCC) technology
NGCC-CCS	Produces electricity from natural gas using NGCC technology with carbon capture and storage
Advanced nuclear	Generates electricity from nuclear energy beyond existing installed plants
Biofuels	Converts biomass into refined oil
Shale oil	Extracts and produces crude oil from oil shale
Coal gasification	Converts coal into a perfect substitute for natural gas

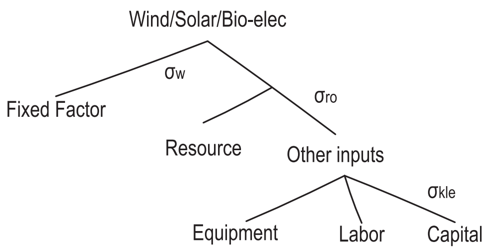

Fig. 2. The CES production structure for wind, solar and biomass electricity technologies.

The overall economic system is closed with a set of market clearance equations that determine the equilibrium prices in the goods and factor markets (Paltsev et al., 2005). We show a simplified expression of the clearance conditions for the goods market (Eq. (7)) and factor market (Eq. (8)).

$$y_{r,i} = \sum_j y_{r,j} \frac{\partial c_{r,j}}{\partial p_{r,i}} + m_r \frac{\partial E_r(p_{r,i}, p_{r,s})}{\partial p_{r,i}} \tag{7}$$

$$k_{r,i} = \sum_j y_{r,j} \frac{\partial c_{r,j}}{\partial w_{r,f}} \tag{8}$$

The model represents production and consumption sectors as nested CES functions (or the Cobb–Douglas and Leontief cases) and is solved recursively in five-year intervals through 2050.

We represent 11 types of advanced technologies in C-GEM as shown in Table 3. Wind, solar, and biomass electricity have similar production structures as shown in Fig. 2. As they produce imperfect substitutes for electricity, a fixed factor is introduced on the top level of CES layers to control the penetration of the technologies (McFarland et al., 2004). Like biofuels, biomass electricity also needs land as a resource input and competes with the agricultural sectors for this resource. Other inputs, including equipment, labor and capital are intermediate inputs and are similar to shale oil and biofuels. Elasticities of substitution are a measure of the ease of shifting among inputs in response to changes in their relative prices. Elasticities in C-GEM are adopted from the MIT EPPA model (Paltsev et al., 2005). The value for σ_w ranges across regions from 0.02-0.06, σ_{ro} is 0.1, and σ_{kle} is 1.

To specify the production cost of these technologies, we set input shares for each technology for each region. This evaluation is based on outside cost estimates, demonstration project information, and expert elicitations (Babiker et al., 2001; Paltsev et al., 2005; Deutch and Moniz, 2007; Moniz et al., 2011; Lanz and Rausch, 2011). A markup factor captures the incremental cost of new technologies compared to traditional fossil generation technologies. All inputs to advanced technologies are multiplied by this markup factor in the model base year, 2007. For electricity technologies and biofuels, we estimate the markups for each technology based on a recent report by the Electric Power Research Institute that compares the technologies on a consistent basis (Electric Power Research Institute, 2011).

In the C-GEM, CO_2 emissions are calculated by applying constant emission factors to the fossil fuel energy flows of coal, refined oil, and natural gas based on the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).[3] The emission factors are assumed to remain constant across regions and over time. CO_2 emissions are introduced as a Leontief input together with fuel consumption. This implies that the reduction of emissions in production sectors can only be achieved by reducing the use of carbon-intensive fuels. In the current version of C-GEM, only CO_2 emissions related to fossil fuel use are tracked.

The C-GEM is parameterized and calibrated based on the latest version of the Global Trade Analysis Project Version 8 (GTAP 8) global database and China′s official national statistics. The GTAP 8 dataset includes consistent national accounts for production and consumption (input–output tables) together with bilateral trade flows for 57 sectors and 129 regions for the year 2007 (Narayanan et al., 2012; Narayanan, 2012). In the C-GEM, we replace the GTAP 8 data with the data from China′s official data sources, including the national input–output tables and energy balance tables for 2007 (National Bureau of Statistics of China, 2008). To maintain the consistency between these two datasets, we have rebalanced the revised global database using the standard least-squares recalibration method. The C-GEM is formulated and solved as a mixed complementarity problem (MCP), in which the equilibrium conditions are expressed as a system of weak inequalities and complementary slackness conditions (between equilibrium variables and equilibrium conditions) (Rutherford, 2005).

4. Scenario description

We design scenarios to assess the impact of China′s current set of renewable electricity policies under several economic growth and renewable electricity cost assumptions. For the economic growth assumptions, we have designed high, low and medium growth trajectories to capture the uncertainty of China′s future economy and its potential impact on the deployment of renewable electricity. We then prepare a "Current Policy" scenario to evaluate the impact of China's targets for the deployment of renewable electricity through 2020 (described in Section 2) under the medium economic growth assumption. We compare the "Current Policy" scenario to a counterfactual "No Policy" scenario that does not include any initiatives to support renewables. Based on our

[3] In this inventory, 94.6 metric tons of CO_2 are emitted per exajoule of coal, while corresponding numbers for oil and natural gas are, respectively, 73.3 and 56.1.

"Current Policy" scenario, we further design two scenarios (high cost and low cost) to simulate the impact of a reduction in renewable electricity costs on long-term deployment. The seven main scenarios considered in this analysis are shown in Table 4.

4.1. Economic growth assumptions

We design high, low, and medium economic growth trajectories that diverge after 2015, assuming that the Twelfth Five-Year Plan growth rate of 7.5% is achieved in all scenarios. After 2015, we design the scenarios to include three potential growth trajectories. The medium growth rate is based on our perspective on China′s future economic situation, The high and low growth scenarios represent roughly 25% above and below the medium growth trajectory through 2035, and the detailed growth rates assumed in each period are shown in Table 5. After 2035, we adjust the growth rate downward, consistent with the developed state of China's economy by that point. These growth rate assumptions produce the GDP and energy use trajectories in the High, Medium, and Low cases shown in Figs. 3 and 4.

4.2. Current policy assumptions

We design a "Current Policy" scenario that achieves the 2020 deployment target for renewable electricity installation by subsidizing its production. In practice, supporting policies are comprehensive, including a feed-in tariff, subsidies to renewable electricity investment, and financing centralized R&D to improve technical efficiency and reduce cost. As the focus of this study is not policy instrument comparison, we use direct subsidies to the production of renewable electricities to represent the aggregated effects of these favorable policies (the current "feed-in tariff" policy is also a type of subsidy instrument). The subsidy rates for wind, solar and biomass electricity are different and derived using the average feed-in tariff prices of wind, solar, and biomass electricity divided by the fossil fuel electricity price, as shown in Table 6.

4.3. Cost and availability assumptions for energy technologies

The incremental cost assumptions for renewable electricity by type are shown in Table 7. Renewable electricity enters the market when it becomes cost competitive with fossil fuel electricity. In our modeling framework this can occur either as fossil fuel prices rise (due to policy or market forces) or if renewable electricity is subsidized.

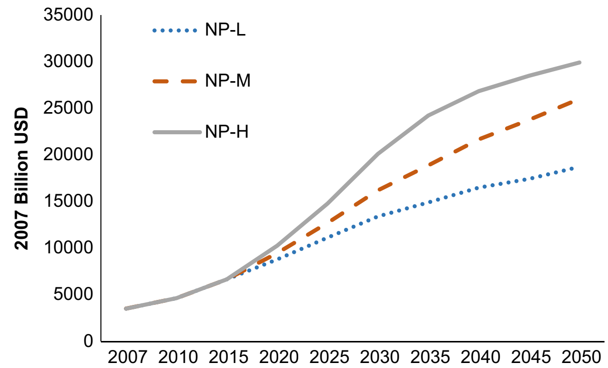

Fig. 3. Economic growth trajectories assuming high (NP-H), medium (NP-M), and low (NP-L) growth under the No Policy (NP) scenario.

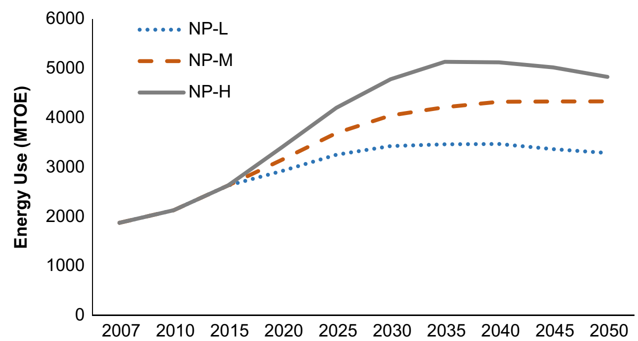

Fig. 4. Energy use assuming high (NP-H), medium (NP-M), and low (NP-L) growth under the No Policy (NP) scenario.

Table 4
Scenario description.

		Renewable electricity policy		
		No Policy (NP)	Current Policy (CP)	Current Policy-Low Cost (CP-LC)
Economic growth	High	NP-H	CP-H	
	Middle	NP-M	CP-M	CP-M-LC
	Low	NP-L	CP-L	

Table 6
The feed-in price and subsidy rate for renewables through 2020.

Renewable electricity	Renewable electricity feed-in tariff (Yuan/kwh)	Fossil fuel electricity sale price (Yuan/kwh)	Subsidy rate (%)
Wind	0.55	0.4	38
Solar	0.95		138
Biomass	0.75		88

Table 7
Incremental cost expressed in percentage terms for each renewable electricity type relative to fossil fuel electricity.

Type	2010–2020	2020–2050	
	All scenarios (%)	Other scenarios (%)	Low cost scenario (%)
Wind	20	20	10
Solar	100	100	50
Biomass	60	60	30

Table 5
Annualized growth rate assumptions for the low, medium, and high GDP growth trajectories.

	2007–2010 (%)	2010–2015 (%)	2015–2020 (%)	2020–2025 (%)	2025–2030 (%)	2030–2035 (%)	2035–2040 (%)	2040–2045 (%)	2045–2050 (%)
Low	9.3	7.5	5.7	4.8	3.8	2.1	2.0	1.1	1.4
Medium	9.3	7.5	7.3	6.0	5.0	3.1	2.8	1.9	1.8
High	9.3	7.5	9.0	7.6	6.3	3.8	2.1	1.2	1.0

Note: Annualized growth rate assumptions are set for the specified five-year interval.

Table 8
The share of renewable electricity in total power generation in the Current Policy scenarios by high (CP-H), middle (CP-M) and low growth (CP-L) trajectories.

	2010 (%)	2015 (%)	2020 (%)	2030 (%)	2050 (%)
CP-H	1.9	4.5	6.6	7.9	23.7
CP-M	1.9	4.5	7.3	4.7	16.7
CP-L	1.9	4.5	7.7	3.3	7.4

To simulate realistic rates of adoption once renewable electricity becomes cost competitive, we included an additional resource input in the production function of each renewable electricity type that simulates costs and constraints associated with initial expansion. This resource input is a function of the renewable energy output and the total electricity sector output, as shown in Eq. (9) below (McFarland et al., 2004). This resource input, which is parameterized for each renewable electricity type, is treated identically in all scenarios (Paltsev et al., 2005; Karplus et al., 2010).

$$F_{res,t} = F_{res,t-1} + f(Y_{renew}, Y_{elec}) \tag{9}$$

where $F_{res,t}$ is the resources factor at time t, $f(Y_{renew}, Y_{elec})$ is the incremental resource supply in the new period, which is a function of renewable electricity output Y_{renew} and total electricity output Y_{elec}.

Renewable energy subsidies are often justified as early stage technology support, allowing renewable energy developers to gain experience and scale up production in ways that effectively reduce the future cost. In the CP-M-LC scenario, we assume the subsidized development of renewable electricity leads to lower costs after 2020, reducing the incremental cost of each technology by at least half. In this scenario, the wind markup is 10% (compared to 20%), solar is 50% (compared to 100%), and biomass markup is 30% (compared to 60%). In the other six scenarios we assume that the markup on renewable electricity relative to conventional fossil generation stays constant over time.

Both No Policy and Current Policy cases include growth assumptions for nuclear and hydro which are set forth in government plans.[4] As we are interested in the impact of supporting renewable electricity specifically, we do not explore alternative cost or availability assumptions for nuclear, hydro, and conventional fossil generation.

5. Results

We now consider the impact of the renewable electricity targets against the background of the three alternative GDP growth trajectories. As expected, we find that the level of GDP growth results in different levels and shares of renewable electricity deployment. The share of generation from renewable electricity sources in the Current Policy scenarios for each of the GDP growth trajectories is shown in Table 8.

For each scenario, we consider the impact of renewable subsidies on energy use, CO_2 emissions, and economic growth. We find that through 2020, while renewable electricity subsidies result in an increase in renewable electricity, the impact on future CO_2 emissions in China is relatively modest. This is partly because renewable energy displaces some fossil fuel use in the electricity sector and puts downward pressure on fossil fuel prices, leading to increased use in other sectors. We further find that if the cost of renewable electricity is successfully reduced during the subsidy period, renewable sources will compete successfully without subsidies through 2050 and supply a much larger share of the primary energy mix in China. However, our analysis suggests that subsidies alone will not be sufficient to realize the CO_2 emissions reduction potential available from renewable energy in China. Instead, it underscores the importance of considering impacts on the integrated energy-economic system when designing renewable energy policies.

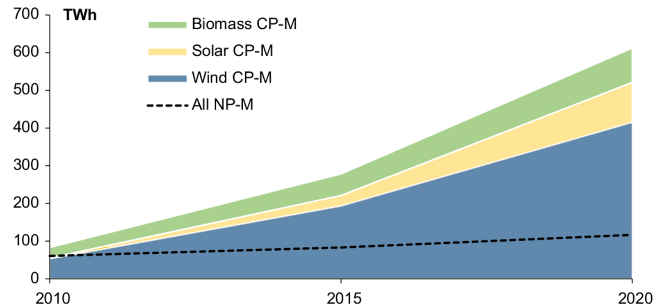

Fig. 5. Renewable energy generation in the Current Policy (CP-M) scenario under the medium GDP growth assumption and relative to total renewable generation in the No Policy (NP-M) scenario (dashed black line).

5.1. Renewable electricity growth under policy scenarios

Current policies result in significant growth in renewable electricity under all three GDP growth scenarios. In all scenarios, renewable electricity growth follows the target trajectory through 2020, remaining significantly above the level of renewable energy generation under the No Policy scenario (Fig. 5). After 2020, the differences between the No Policy and Current Policy scenarios are less pronounced. In both the No Policy and Current Policy, the renewable growth trajectories diverge under different growth assumptions and affect both the total energy mix and the relative prices of energy types. In the Current Policy scenario, as subsides are phased out between 2020 and 2030, the total generation from renewable electricity begins to fall, and its contribution into the future depends on its cost competitiveness relative to other generation types.

Fig. 6 compares the renewable electricity generation and its share of total electricity use in 2010, 2020, 2030, and 2050 in the non-subsidized case (No Policy) and subsidized case (Current Policy). With subsidies, we observe a large expansion of wind power, in which growth is three times as fast as in the No Policy case. Subsidies also effectively increased the share of solar generation, but because of its high relative cost, solar contributes on a smaller scale compared to wind under the current subsidy levels.

5.2. Impact of renewable electricity subsidies on CO_2 emissions reductions

Our modeling framework allows us to assess the impact that current renewable electricity subsidies will have on total CO_2 emissions from China's energy system. We consider two periods, 2010 to 2020 and 2020 to 2050 and compute the total reduction achieved, focusing only on the medium growth case for simplicity.[5] We compare this to an "idealized" reduction that assumes that all new renewable electricity generation displaces fossil fuel generation and that there is no incentive to increase use of

[4] The government plan for the installed capacity of nuclear is 40 GW in 2015 and 58 GW in 2020; of hydro is 290 GW in 2015 and 420 GW in 2020.

[5] Using the low or high GDP growth assumption does not change the policy results significantly.

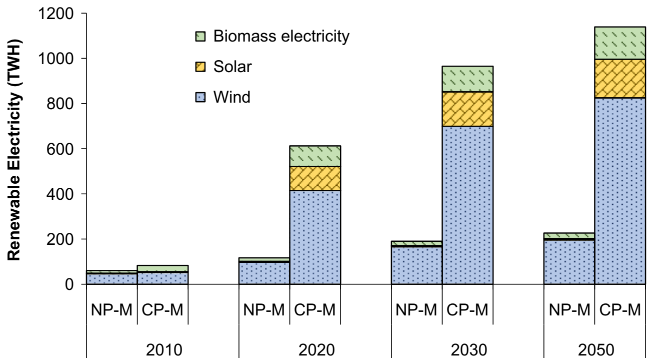

Fig. 6. Renewable electricity output in the NP-M and CP-M scenarios under the medium economic growth assumption.

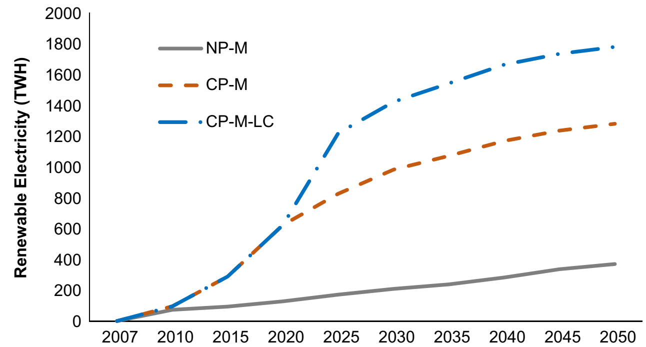

Fig. 7. Growth in renewable electricity in the No Policy (NP-M), Current Policy (CP-M), and Current Policy+Low Cost (CP-M-LC) scenario under the medium GDP growth assumption.

Table 9
Annual reduction in China's total CO_2 emissions due to current policy, relative to the no policy scenario (mmt).

	2015	2020	2025	2030	2035	2040	2045	2050
Idealized reduction with no economy-wide effects	144	342	436	480	506	528	525	518
Simulated reduction with economy-wide effects (C-GEM)	141	304	363	387	386	380	358	337

carbon-intensive fuels in other sectors as a result of displacing them from electricity.

We compute the CO_2 emissions reduction achieved in the medium growth case by comparing the No Policy and Current Policy scenarios. We find that the renewable electricity target has the effect of lowering emissions intensity by 1.7% in 2015 and by 3.1% in 2020 compared to the No Policy scenario. From 2020 to 2050, we find an average 3.2% reduction in CO_2 emissions intensity after 2020 in the Current Policy scenario (although no targets are being imposed in this period).

In terms of the total CO_2 emissions reduction, the model predicts cumulative CO_2 emissions will be lower by 1514 million metric tons (mmt) (1.8%) over the period 2010 to 2020. We find that a target early on (2010-2020) has a modest effect on lowering emissions over the 2020 to 2050 period. Cumulative emissions from 2020 to 2050 are slightly lower with early renewable electricity deployment (Current Policy Scenario) relative to a No Policy scenario by 10,972 mmt or 3%.

We find that despite renewable electricity expansion in the Current Policy scenario, CO_2 emissions reductions may not be as large as a simple calculation would predict. For this analysis we use a CGE model with energy system detail in order to capture how the renewable subsidy policy interacts with fuel prices, fuel demand, and the broader evolution of the energy-economic system and its associated CO_2 emissions. The total CO_2 emissions reductions measured using this model will reflect how the policy affects underlying energy prices, and how these effects are transmitted across markets through economic activity and trade linkages in China and on a global scale. The objective is to capture the real-world mechanisms that will affect the impact of renewable energy on CO_2 emissions outcomes. These effects are omitted from many models. It is instructive to compare the results of the model simulation to a calculation that focuses on renewable electricity only and assumes that renewable electricity displaces fossil energy use and associated CO_2 emissions without affecting energy use in other sectors, which can be taken as an “ideal” upper bound on emissions reductions. Table 9 compares an "idealized" calculation that assumes changes are limited to the electricity sector to our model simulation results. The simulated reduction is sizable using our model in 2015 and 2020 (although still smaller than ideal). After the subsidies are phased out in 2020, we find that the simulated reduction in CO_2 emissions is 17% to 35% lower than the "idealized" reduction as a result of the stimulating effect of less expensive renewable energy on economic growth and emissions leakage. In the model, we further observe that the prices for fossil generation types remain lower under the Current Policy scenario for much of the next half century, which provides an incentive to increase their use. The result suggests that once dynamics in the broader economic and energy system are taken into account, the total CO_2 emissions reduction predicted due to the deployment of renewable electricity is significantly smaller than the "idealized" reduction predicted in the absence of economy-wide effects.

5.3. *Impact of a cost reduction for renewable electricity after 2020*

Earlier scenarios assumed that the markup for renewable electricity remains constant after 2020. If we instead assume that the *n*th plant cost for each renewable electricity type will drop significantly after 2020 (by adopting the low cost technology assumptions described above), we find that renewable electricity generation increases significantly by 2050 as the cost of renewable electricity falls (as shown in Fig. 7). This increase is apparent: under the Current Policy+Low Cost scenario, we find that renewable generation increases to 14.3% of the total compared to 10% under the Current Policies only and 2% under the No Policy scenario (as shown in Fig. 8).

We also study the impact of the assumed cost reduction on renewable generation by type and on total CO_2 emissions relative to the Current Policy case with no cost reduction. Focusing on the period 2010 to 2050, we find that the cumulative CO_2 reduction is significantly larger, reaching 12,487 mmt or 2.8% relative to the No Policy scenario. As shown in Table 10, an average 4.2% emission reduction is observed in the Current Policy+Low Cost scenario. The difference in CO_2 emissions in the Current Policy and Current Policy+Low Cost (medium GDP growth) scenarios are shown in Fig. 9.

In the low cost scenario, it is important to realize that the leakage effects associated with the supply-side cost shock are also more pronounced. This result is consistent with the fact that in the Current Policy+Low Cost scenario we find that in 2050 the electricity price is 4% lower and the coal price is 10% lower relative to the Current Policy scenario.

6. Conclusion

China′s renewable energy policy is currently focused on increasing the installed capacity of wind, solar, and biomass-

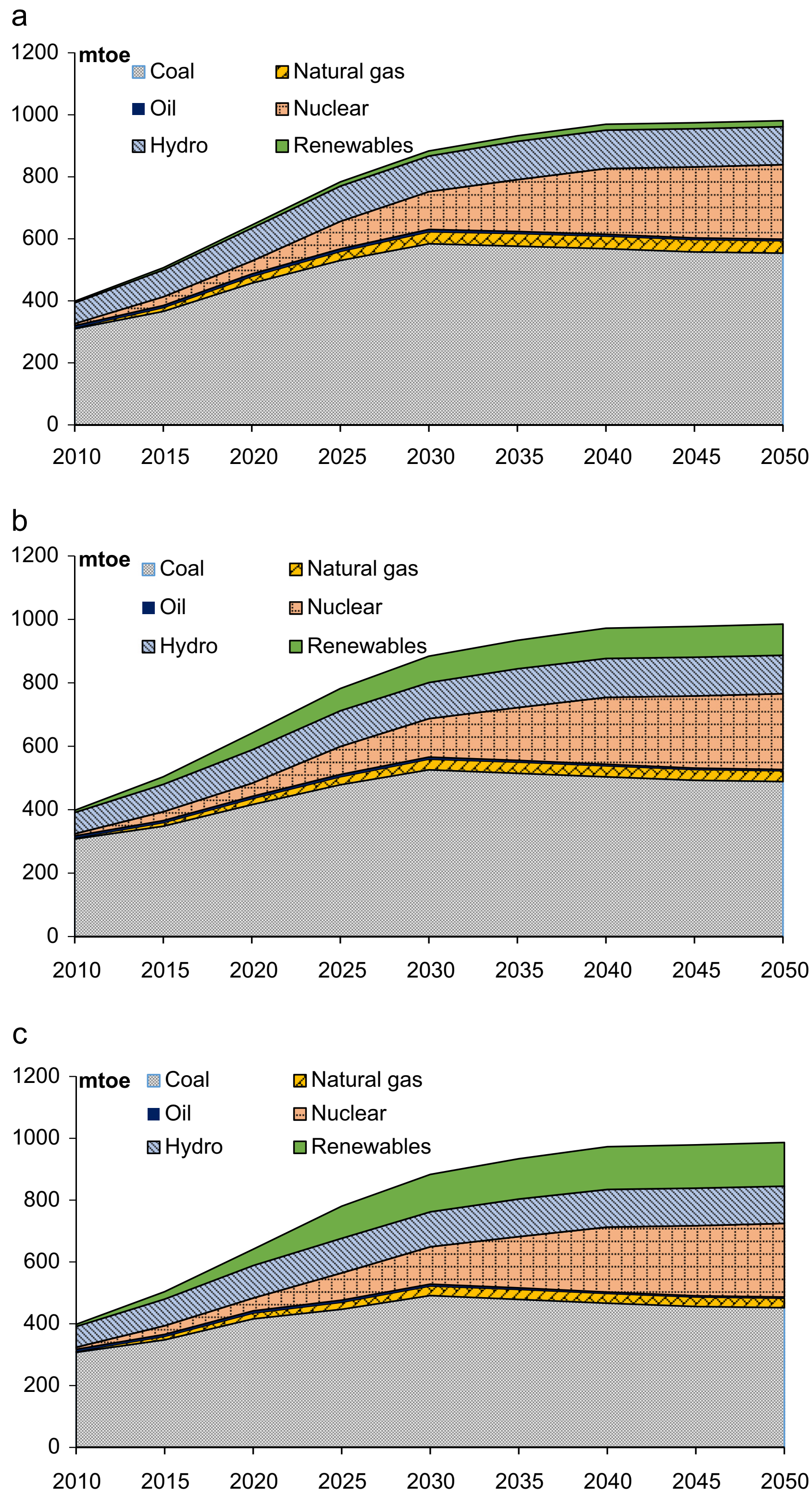

Fig. 8. The evolution of the electricity generation mix through 2050 in the (a) NP-M scenario, (b) CP-M scenario, and (c) CP-M-LC scenario. Energy units are million tons of oil equivalent (mtoe).

based electricity. When the Current Policy is simulated in the C-GEM model, we find that the policy does have the effect of increasing the renewable electricity generation from 2010 to 2020 in both absolute (from 95 TWh to 623 TWh) and relative terms (from 1.8% to 8.2% of total generation). Due to the introduction of renewable electricity over the period 2010 to 2020, overall CO_2 emissions intensity falls by a modest 2%.

After 2020 the impact of renewable electricity largely depends on the economic growth and cost assumption. We find that high economic growth results in higher energy demand and prices,

Table 10
Impact on renewable electricity generation and CO_2 emissions reductions (scenarios NP-M, CP-M, and CP-M-LC, broken down by type).

Scenario	Renewable electricity type	Electricity generation (mtoe)*			
		2015	2020	2030	2050
NP-M	Wind	67	97	166	196
	Solar	3	4	5	6
	Biomass	14	15	19	24
CP-M	Wind	193	415	699	825
	Solar	28	106	152	171
	Biomass	57	91	113	143
	CO_2 emissions reduction (%)	1.7	3.1	3.2	2.7
CP-M-LC	Wind	193	415	653	772
	Solar	28	106	599	674
	Biomass	57	91	153	194
	CO_2 emissions reduction (%)	1.7	3.1	5.2	4.3

* Electricity generation is measured in terms of million tons of oil equivalent (mtoe).

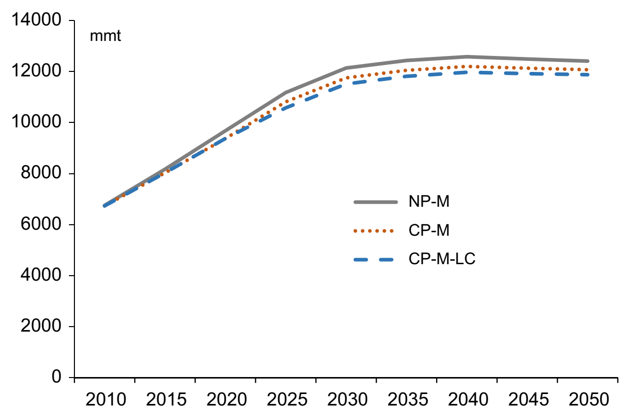

Fig. 9. Total CO_2 emissions in the No Policy (NP-M), Current Policy (CP-M), and Current Policy+Low Cost (CP-M-LC) scenario under the medium growth assumption.

which creates more favorable conditions for renewable electricity adoption. The low economic growth assumption, by contrast, alleviates the price pressure on fossil fuels and so renewable sources are less competitive—but total primary energy use and CO_2 emissions are also lower overall. In this respect, renewable electricity delivers low cost substitute when fossil demand is high, but playing a less prominent role when fossil fuel demand is lower. If renewable electricity is to respond in this way, it will be important to allow the prices of fossil fuels to reflect their true cost of production. In our model we assume that energy prices are determined by the market. If we assume instead that fuel or electricity end use prices are regulated by the government (which is currently the case in China), we expect that growth in renewable electricity will be lower over the time period we consider.

Subsidies for renewable electricity in China impose a cost to the government. Some point out that these early investments could result in learning-by-doing that reduces the cost of renewable electricity in future periods. Here we capture this possibility by simulating a scenario in which costs fall after 2020, for instance through materials substitution, manufacturing advances, or additional reductions in installation costs. After 2020, the cost reduction has a large impact on the level of renewable electricity adoption. With higher levels of renewable electricity adoption, the impact on CO_2 emissions is also larger, while electricity prices do not rise as much as they would have in the absence of a cost reduction.

Nevertheless, when it comes to reducing CO_2 emissions, we find that supply-side policies such as the current renewable electricity target may have a more modest impact on total emissions than many expect, due to offsetting leakage effects. In both the Current Policy scenario and the Current Policy+Low Cost scenario, we find that "idealized" reductions delivered by additional renewable capacity are partially offset in future years by increased use of fossil fuels in other sectors of the economy. The greater the contribution of subsidized renewables to electricity generation, the greater the downward pressure on fossil fuel prices, and the greater the leakage effects. Policymakers would be well served to consider the impact of these offsetting effects as they design complementary or alternative policies to bring renewable electricity into the generation mix. One such approach would be to include electricity and other sectors under a cap-and-trade system for CO_2 emissions, an approach that is already being piloted on a limited basis in some areas in China.

Finally, we consider the contribution of the renewable electricity target to China's national carbon and non-fossil energy goals. Our model results suggest that the renewable electricity targets will make a relatively modest contribution to the Twelfth Five-Year Plan carbon intensity reduction goal of 17%, accounting for about 12% of the total reduction in 2015 (achieving a total national carbon intensity reduction of 2%). We point out that if the "idealized" reduction calculation is used instead, this reduction looks much larger. This analysis cautions against the use of sector-by-sector calculations of CO_2 emissions reduction impacts that ignore broader economy-wide interactions. A policy approach that covers all sectors and allows substantial flexibility to reduce CO_2 emissions at lowest cost–such as an emissions trading system – would do more to prevent emissions leakage and ensure reductions in CO_2 emissions are achieved over the long term.

Acknowledgements

We acknowledge the support of the French Development Agency (AFD), Eni S.p.A., ICF International, and Shell, founding sponsors of the MIT-Tsinghua China Energy and Climate Project. We acknowledge the support of the Ministry of Science and Technology of China through the Institute for Energy, Environment, and Economy at Tsinghua University, and the support from Graduate School of Tsinghua University and Rio Tinto China, which supported Tianyu Qi's doctoral research as a visiting scholar at the Massachusetts Institute of Technology. The authors are also grateful for support provided by the Social Science Key Research Program from the National Social Science Foundation of China Grant No. 09&ZD029. We acknowledge the contribution of the MIT Joint Program on the Science and Policy of Global Change through a combination of government, industry, and foundation funding. This work is also supported by the U.S. Department of Energy Integrated Assessment Grant (DE-FG02-94ER61937).

References

Babiker, H.M., Reilly, J.M., Mayer, M., Richard, S.E., Ian Sue Wing, Hyman, R.C., 2001. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. MIT Joint Program on the Science and Policy of Global Change, Report 71.
China Greentech Initiative, 2011. The China Greentech Report. (Available at ⟨http://www.china-greentech.com/report⟩).
Deutch, J.M., Moniz, E.J., 2007. The Future of Coal-Options for a Carbon-Constrained World. MIT Press, Cambridge, Mass. (Available at ⟨http://web.mit.edu/coal/⟩).
Electric Power Research Institute, 2011. Program on Technology Innovation: Integrated Generation Technology Options. Palo Alto, CA. 1022782. (Available at ⟨http://integrating-renewables.org/wp-content/uploads/LINK-E-CCUG-000-000000001022782.pdf⟩).
Huo, M.L., Zhang, X.L., He, J.K., 2011. Photovoltaic module price dynamics: empirical evidences from case studies. J. Tsinghua Univ. Sci. Technol. 51, 796–801.

Institute for Industrial Productivity, 2012. Industrial Efficiency Policy Database, China. (Available at ⟨http://iepd.iipnetwork.org/⟩).
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (Available at ⟨http://www.ipcc-nggip.iges.or.jp/public/2006gl⟩/).
Karplus, V.J., Sergey, P., Reilly, J.M., 2010. Prospects for plug-in hybrid electric vehicles in the United States and Japan: a general equilibrium analysis. Trans. Res. A: Pol. Pract. 44, 620–641.
Lanz, B., Rausch, S., 2011. General equilibrium, electricity generation technologies and the cost of carbon abatement: a structural sensitivity analysis. Energy Econ. 33, 1035–1047.
Liu, L., Liu, C., Wang, J., 2013. Deliberating on renewable and sustainable energy policies in China. Renewable Sustainable Energy Rev. 17, 191–198.
Liu, W., Lund, H., Mathiesen, B.V., 2011. Large-scale integration of wind power into the existing Chinese energy system. Energy 36, 4753–4760.
Matus, K., Nam, K.M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Global Environ. Change: Hum. Policy Dimens. 22, 55–66.
McFarland, J.R., Reilly, J.M., Herzog, H.J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Econ. 26, 685–707.
Moniz, E.J., Jacoby, H.D., Meggs, A.J.M., 2011. The Future of Natural Gas. MIT Press, Cambridge, Mass. (Available at ⟨http://mitei.mit.edu/system/files/NaturalGas_Report.pdf⟩).
Narayanan, B., 2012. GTAP 8 Data Base Documentation—Chapter 3: What′s New in GTAP 8? (Available at ⟨https://www.gtap.agecon.purdue.edu/resources/download/6038.pdf⟩).
Narayanan, B., Betina, D., Robert, M., 2012. GTAP 8 Data Base Documentation—Chapter 2: Guide to the GTAP Data Base.
National Bureau of Statistics of China, 2008. 2007 China Energy Statistical Yearbook. China Statistics Press, Beijing.
Paltsev, S., Morris, J., Cai, Y., Karplus, V., Jacoby, H., 2012. The role of China in mitigating climate change. Energy Econ. 34, S444–S450.
Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J.R., Sarofim, M., et al., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, Report 125.
Qi, T., Zhou, L., Zhang, X., Ren, X., 2012. Regional economic output and employment impact of coal-to-liquids (CTL) industry in China: an input–output analysis. Energy 46, 259–263.
Renewable Energy World, 2005. China Passes Renewable Energy Law. (Available at ⟨http://www.renewableenergyworld.com/rea/news/article/2005/03/china-passes-renewable-energy-law-23531⟩).
Rutherford, T.F., 2005. GTAP6inGAMS: The Dataset and Static Mode. (Available at ⟨http://www.mpsge.org/gtap6/gtap6gams.pdf⟩.).
Santalco, A., 2012. How and when China will exceed its renewable energy deployment targets. Energy Policy Renewable Energy China 51, 652–661.
The World Bank, China Ministry of Environmental Protection, 2007. Cost of Pollution in China: Economic Estimates of Physical Damages. (Available at ⟨http://siteresources.worldbank.org/INTEAPREGTOPENVIRONMENT/Resources/China_Cost_of_Pollution.pdf⟩).
Wang, Z., Qin, H., Lewis, J.I., 2012. China′s wind power industry: policy support, technological achievements, and emerging challenges. Energy Policy 51, 80.
Yuan, J., Hou, Y., Xu, M., 2012. China′s 2020 carbon intensity target: consistency, implementations, and policy implications. Renewable Sustainable Energy Rev. 16, 4970–4981.
Zhao, X., Wang, J., Liu, X., Liu, P., 2012. China′s wind, biomass and solar power generation: what the situation tells us? Renewable Sustainable Energy Rev. 16, 6173–6182.

MIT Joint Program on the Science and Policy of Global Change - REPRINT SERIES

FOR THE COMPLETE LIST OF REPRINT TITLES: http://globalchange.mit.edu/research/publications/reprints

2013-27 Economic and emissions impacts of renewable fuel goals for aviation in the US, Winchester, N., D. McConnachie, C. Wollersheim and I.A. Waitz, *Transportation Research Part A: Policy and Practice,* 58(2013):116–128 (2013)

2013-28 An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0), Monier, E., J.R. Scott, A.P. Sokolov, C.E. Forest and C.A. Schlosser, *Geosci. Model Dev.* 6: 2063–2085 (2013)

2013-29 Characterization of the wind power resource in Europe and its intermittency, Cosseron, A., U.B. Gunturu and C.A. Schlosser, *Energy Procedia,* 40(2013): 58–66 (2013)

2013-30 Climate Change and Emissions Impacts on Atmospheric PAH Transport to the Arctic, Friedman, C.L., Y. Zhang and N.E. Selin, *Environmental Science & Technology,* online first, doi: 10.1021/es403098w (2013)

2013-31 Cost Concepts for Climate Change Mitigation, Paltsev, S. and P. Capros, *Climate Change Economics,* 4(Suppl.1): 1340003 (2013)

2013-32 Insights and issues with simulating terrestrial DOC loading of Arctic river networks, Kicklighter, D.W., D.J. Hayes, J.W. McClelland, B.J. Peterson, A.D. McGuire and J.M. Melillo, *Ecological Applications,* 23(8): 1817–1836 (2013)

2013-33 A Contemporary Carbon Balance for the Northeast Region of the United States, Lu X., D.W. Kicklighter, J.M. Melillo, P. Yang, B. Rosenzweig, C.J. Vörösmarty, B. Gross and R.J. Stewart, *Environmental Science & Technology,* 47(3): 13230–13238 (2013)

2013-34 European-Led Climate Policy versus Global Mitigation Action: Implications on Trade, Technology, and Energy, De Cian, E., I. Keppo, J. Bollen, S. Carrara, H. Förster, M. Hübler, A. Kanudia, S. Paltsev, R.D. Sands and K. Schumacher, *Climate Change Economics,* 4(Suppl. 1): 1340002 (2013)

2013-35 Beyond 2020—Strategies and Costs for Transforming the European Energy System, Knopf, B., Y.-H.H. Chen, E. De Cian, H. Förster, A. Kanudia, I. Karkatsouli, I. Keppo, T. Koljonen, K. Schumacher and D.P. van Vuuren, *Climate Change Economics,* 4(Suppl. 1): 1340001 (2013)

2013-36 Estimating regional methane surface fluxes: the relative importance of surface and GOSAT mole fraction measurements, Fraser, B., P.I. Palmer, L. Feng, H. Boesch, A. Cogan, R. Parker, E.J. Dlugokencky, P.J. Fraser, P.B. Krummel, R.L. Langenfelds, S. O'Doherty, R.G. Prinn, L.P. Steele, M. van der Schoot and R.F. Weiss, *Atmospheric Chemistry and Physics,* 13: 5697–5713 (2013)

2013-37 The variability of methane, nitrous oxide and sulfur hexaflouride in Northeast India, Ganesan, A.L., A. Chatterjee, R.G. Prinn, C.M. Harth, P.K. Salameh, A.J. Manning, B.D. Hall, J. Mühle, L.K. Meredith, R.F. Weiss, S. O'Doherty and D. Young, *Atmospheric Chemistry and Physics,* 13: 10633–10644 (2013)

2013-38 Integrated economic and climate projections for impact assessment, Paltsev, S., E. Monier, J. Scott, A. Sokolov and J.M. Reilly, *Climatic Change*, October 2013, doi: 10.1007/s10584-013-0892-3 (2013)

2013-39 Fiscal consolidation and climate policy: An overlapping generations perspective, Rausch, S., *Energy Economics,* 40(Supplement 1): S134–S148 (2013)

2014-1 Estimating a global black carbon emissions using a top-down Kalman Filter approach, Cohen, J.B. and C. Wang, *Journal of Geophysical Research—Atmospheres,* 119: 1–17, doi: 10.1002/2013JD019912 (2014)

2014-2 Air quality resolution for health impact assessment: influence of regional characteristics, Thompson, T.M., R.K. Saari and N.E. Selin, *Atmospheric Chemistry and Physics,* 14: 969–978, doi: 10.5194/acp-14-969-2014 (2014)

2014-3 Climate change impacts on extreme events in the United States: an uncertainty analysis, Monier, E. and X. Gao, *Climatic Change,* doi: 10.1007/s10584-013-1048-1 (2014)

2014-4 Will economic restructuring in China reduce trade-embodied CO_2 emissions? Qi, T., N. Winchester, V.J. Karplus, X. Zhang, *Energy Economics,* 42(March): 204–212 (2014)

2014-5 Assessing the Influence of Secondary Organic versus Primary Carbonaceous Aerosols on Long-Range Atmospheric Polycyclic Aromatic Hydrocarbon Transport, Friedman, C.L., J.R. Pierce and N.E. Selin, *Environmental Science and Technology,* 48(6): 3293–3302 (2014)

2014-6 Development of a Spectroscopic Technique for Continuous Online Monitoring of Oxygen and Site-Specific Nitrogen Isotopic Composition of Atmospheric Nitrous Oxide, Harris, E., D.D. Nelson, W. Olszewski, M. Zahniser, K.E. Potter, B.J. McManus, A. Whitehill, R.G. Prinn and S. Ono, *Analytical Chemistry,* 86(3): 1726–1734 (2014)

2014-7 Potential Influence of Climate-Induced Vegetation Shifts on Future Land Use and Associated Land Carbon Fluxes in Northern Eurasia, Kicklighter, D.W., Y. Cai, Q. Zhuang, E.I. Parfenova, S. Paltsev, A.P. Sokolov, J.M. Melillo, J.M. Reilly, N.M. Tchebakova and X. Lu, *Environmental Research Letters,* 9(3): 035004 (2014)

2014-8 Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply, Arent, D., J. Pless, T. Mai, R. Wiser, M. Hand, S. Baldwin, G. Heath, J. Macknick, M. Bazilian, A. Schlosser and P. Denholm, *Applied Energy,* 123(June): 368–377 (2014)

2014-9 The energy and CO_2 emissions impact of renewable energy development in China, Qi, T., X. Zhang and V.J. Karplus, *Energy Policy*, 68(May): 60–69 (2014)

MIT Joint Program on
The Science and Policy of Global Change
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139
USA