

An Integrated Assessment of China's Wind Energy Potential

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Abstract

Computable general equilibrium (CGE) models seeking to evaluate the impacts of electricity policy face difficulties incorporating detail on the variable nature of renewable energy resources. To improve the accuracy of modeling renewable energy and climate policies, detailed scientific and engineering data are used to inform the parameterization of wind electricity in a new regional CGE model of China. Wind power density (WPD) in China has been constructed using boundary layer flux data from the Modern Era Retrospective-analysis for Research and Applications (MERRA) dataset with a 0.5° latitude by 0.67° longitude spatial resolution. Wind resource data are used to generate production cost functions for wind at the provincial level and offshore, incorporating technological parameters and geographical constraints. With these updated wind production cost data to parameterize the wind electricity option in a CGE model, an illustrative policy analysis of the current feed-in tariff (FIT) for wind electricity is performed. Assuming a generous penetration rate and no interprovincial interconnection, we find that the contribution of wind to total electricity generation is 213 TWh, reducing CO₂ emissions by 3.5%. We discuss the relative merits of the FIT by province. Our analysis shows how wind electricity resource can be differentiated based on location and quality in a CGE model and applied to a analyze climate and energy policies.

1. Introduction

China's energy demand has grown by 150% over the past decade, surpassing the United States in 2010 to become the world's largest energy user. The majority of this growth has come from a heavy reliance on coal, which was 70% of total primary energy use and 78% of electricity generation in 2011 (NBS, 2012; CEC, 2012). Estimated costs of environmental damage from these types of activities range from 4–7% of China's annual economic output (World Bank and China SEPA, 2007). To reduce these adverse impacts and to combat climate change, China has actively scaled up deployment of renewable energy. China leads the world in installed capacity of renewable energy and in wind generation capacity (REN21, 2012). Growth in wind generation surpassed growth in coal-fired electricity for the first time ever in 2012 (CEC, 2013).

Large penetrations of wind energy present new challenges for grid operators and policy-makers interested in meeting ambitious climate change mitigation goals. While wind energy has low variable costs, the inherent uncertainty in its resource availability has the potential to drive up system-wide balancing costs, especially when the grid mix is primarily inflexible generation such as coal-fired power. In addition, the most economical resources are also highly distributed and often far from load centers, adding to costs of transmission infrastructure. These characteristics complicate analysis of both economy-wide and electricity sector-specific policy proposals currently under discussion in China.

Globally, the International Energy Agency estimates that over \$38 trillion of new energy infrastructure will need to be built through 2035 to meet growing demand (IEA, 2011). Because of the long construction and operational lifetimes of conventional power plants and transmission infrastructure, the choice of investments made in Beijing and New Delhi today will have a large impact on the future grid mix available to accommodate increasing renewable penetration. These policy decisions require sophisticated modeling techniques that incorporate economic, technical and resource constraints.

This paper presents a novel method of analyzing climate policies using a computable general equilibrium (CGE) framework and detailed wind characterization using Modern Era Retrospective-analysis for Research and Applications (MERRA) data. Technical, geographic and financial characteristics of wind projects are explicitly accounted for in provincial wind cost production functions, updating previous assessments of wind energy potential in China. Offshore wind resources are also characterized, but are not incorporated into the general economy model. The methodology is used to evaluate wind deployment in 2020 under scenarios of an increased feed-in-tariff.

1.1 China's renewable energy policies and projected deployment of wind

China has experimented with a range of policy instruments to encourage renewable energy deployment and reform energy system institutions (IIP, 2012). China's *National Renewable Energy Law of 2006* and regulations issued under it have instituted feed-in tariffs for wind, solar and biomass, tax relief and direct subsidies for developers, and public support for research and development (NDRC, 2006; ERI, 2010; Kang et al., 2012). It appears likely that China will implement renewable power quotas for 2015 for major generators and grid companies, formulated as the percentage of total generation coming from non-hydro renewable energy (Schuman & Lin, 2012). China currently aims to install 200 gigawatts (GW) of wind and 50 gigawatts of solar by 2020 (see Table 1).

Renewable energy targets	Grid-connected capacity (GW)		
	2012	2015	2020
Wind	62	104	200
Solar	3.1	21	50
Biomass	4.4	13	30

Table 1. China's targets for renewable energy development through 2020. Sources: REN21 (2012), NEA (2012), NDRC (2012).

Wind energy benefits from a handful of stable central government incentives, including (1) four resource-dependent feed-in-tariff levels supported through a nationwide electricity surcharge (see Figure 1); and (2) preferential value-added tax (VAT) rates during the first several years of a project's life (Wang et al., 2012). The *Renewable Energy Law* mandates grid companies to provide prompt connection service and accept all electricity from a renewable energy project except in the case of grid stability issues.

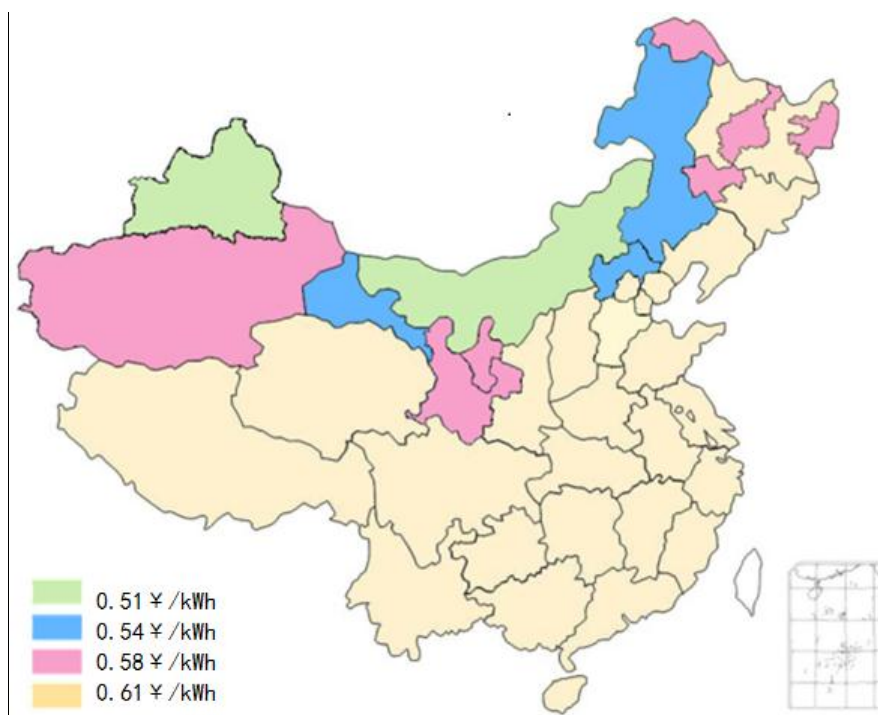


Figure 1. Wind feed-in-tariffs for wind projects. (RMB / kWh)

1.2 Current state of wind connection and integration challenges

Electricity generating technologies place a number of constraints on efficient system operation. For conventional generators, maximum ramping rates and associated ramp costs, minimum shutdown and startup times, and output-dependent heat rates, among other properties, are important to consider in week-ahead planning. For renewable resources such as wind, solar and run-of-the-river hydropower, these include minimum and maximum output thresholds, as well as natural intermittency. Wind integration challenges arise from frequent ramping requirements and unpredictability of wind resources interacting with the technical limits of conventional generators, which results in efficiency losses and grid stability concerns (Porter et al., 2007).

Integrating renewable electricity into China's power grid has been a well-documented challenge. Over the period from 2006 to 2012, installed wind capacity expanded rapidly, but ensuring its contribution to the nation's generation mix has been less straightforward for technical, economic, and institutional reasons (Liu and Kokko, 2010). In general, policies have rewarded wind facility construction, creating only weak incentives to consider wind characteristics at the construction location. As a result, at the end of 2011, around 25% of wind capacity was not yet connected to the grid (CREIA et al., 2012). In addition, grid-connected wind capacity has seen decreasing capacity factors from curtailment. In 2012, while wind contributed only 2% of total electricity supply, around 20 TWh of wind was spilled (an effective curtailment rate of 17%), and reaching 40–50% in some areas (CEC, 2013; NEA, 2013; Qi, 2013; Marcacci, 2012). By comparison, the Electricity Reliability Council of Texas (ERCOT) met 8.5% of supply with wind in 2011, while curtailing 8.5% (ERCOT, 2012; Wiser & Bolinger, 2012). In an attempt to strengthen oversight and ensure construction quality for long-term project viability,

authority for project approval has been reassigned from the local to the central government level (Xu and Alleyne, 2013).

Researchers and grid operators attempting to quantify the system-wide effects of increased renewable energy penetration have traditionally estimated costs in three ways: involuntary ramping of thermal units and other inflexible generation units, maintenance of additional reserves or backup capacity, and ancillary services such as frequency regulation. A survey of studies in the United States found additional ancillary service costs from increased wind penetration ranging from \$1–\$5/MWh (Porter et al., 2007). Another large body of research focuses on optimal generation mixes as more renewable resources are brought online. A study of the resilience of the Chinese grid found a cutoff at around 26% penetration of wind into the grid (by production), above which integration costs become limiting (Liu et al., 2011).

Since these integration costs are not localized, there is a large uncertainty in attributing them solely to wind power. In particular, existing methods tend to discount the inflexibility of conventional resources, leading some researchers to look for generalized metrics of “flexibility” for all generating types (Ma et al., 2013). Coal, accounting for 80% of China’s electricity production and projected to continue increasing in absolute terms, plays a large role in grid integration challenges. As coal’s relative share varies significantly by region, and is expected to decline nationally in response to nuclear, natural gas and large hydropower build-out, the specific integration challenges will be highly contextual and location-specific.

1.3 Motivation for this study

The rapid increase of wind electricity generation in China expected over the next decade will face several hurdles, ranging from siting and geographical concerns, grid connection and integration costs, to macro-economic effects of fuel substitution. In order to assess policies addressing these concerns, computable general equilibrium (CGE) models are a preferred choice over partial equilibrium approaches for the electricity sector alone, due to their resolution of aggregated, economy-wide effects (Lanz and Rausch, 2011). Commonly used simplified CGE representations, however, may be inconsistent with technology and fuel substitution details afforded by a detailed bottom-up electricity sector model. In addition, CGE models typically assume only a representative profile for wind generation without disaggregation by region. This study improves on the wind resource profile and provides evidence for the need to incorporate more technology characterizations to explain real-world observations in China.

2. Literature review

2.1 Previous assessments of China’s wind resources

Detailed assessments of wind resources in China have only recently become available. The National Renewable Energy Laboratory has several publicly available wind resource assessments that vary in terms of their geographic coverage. NREL (2007a) used satellite and upper-air measurements to construct 1-km² resolution maps of wind power density in eastern China. Elliott et al. (2002) included ground station measurements to construct 200-meter resolution maps of portions of southeastern China. NASA has conducted a global wind assessment with 1-degree spatial resolution (approx. 100 km x 80 km at mid-latitudes), providing average wind speeds

(NASA, 2009). NREL (2007b) provides global offshore wind speed and wind power density at 0.25-degree resolution.

McElroy et al. (2009) used a data assimilation system on a five-year model output (2004–2008) from the Goddard Earth Observing System (GEOS-5) to reconstruct mean wind speed and wind power density maps of China at an 80-meter wind turbine hub height. The paper calculated regional capacity factors and levelized costs of electricity, and assessed potential electricity generation. Due to the short observation record available at the time, the paper could not, however, account for interannual variability. The MERRA dataset used in this work also explicitly accounts for boundary layer effects. Hong and Moller (2011) generated 1-km² resolution for feasible offshore wind potential based on NREL wind data, accounting for ocean depth.

2.2 General equilibrium approaches to incorporating intermittent energy sources

CGE models model electricity as a fungible commodity, with the same quality and value regardless of its primary energy source. These models do not track electricity flows, equate supply and demand instantaneously, or incorporate operational characteristics of generating technologies. Therefore, additional information or alternative approaches are generally needed to capture the temporal variability of supply, which is especially important as the relative contribution of renewable electricity to total generation expands.

One such method is for the CGE model to treat renewable electricity as an imperfect substitute to conventional electricity generation (fossil fuel-based, nuclear and hydropower) with a rising resource input cost correlated with the availability and intensity of wind resources. This formulation provides one way of capturing the costs of intermittency and allows gradual penetration of renewables only as prices of other generation technologies rise (Paltsev, Reilly et al. 2005). A second method implemented in a CGE framework creates a piece-wise wind production function, modeling imperfect substitution at low penetrations and requiring back-up capacity (e.g., natural gas-fired) at high penetrations (Morris, Reilly et al. 2010). Additional approaches that have been attempted include disaggregating the electricity commodity sector into several load blocks throughout the year (Rodrigues, Linares et al. 2011). Table 2 reviews briefly these approaches in increasing order of detail.

Basic approach	Backup capacity Require additional flexible generation units (e.g., natural gas) that add to renewable generation costs	Cost penalty Unavailability and intermittency modeled as resource “cost” and substitution penalty of scaling up generation	Load blocks Electricity is differentiated by time and region, according to demand and supply variability	Iterative model Recursively run CGE and external power systems model to minimize bottom-up and top-down deviation
Research application	Morris et al. (2010), Paltsev et al. (2005)	Paltsev et al. (2005)	Rodrigues et al. (2011)	Rausch and Mowers (2012)
Increasing technical detail and model coupling challenges →				

Table 2. Review of approaches to incorporate renewable energy characteristics in CGE models.

2.3 Results of CGE modeling of China's energy and climate policies

This analysis contributes to a growing body of CGE modeling studies focused on the contribution of renewable electricity to low carbon development in China, part of a broader research agenda on the design of energy and climate policy in China. Many studies have applied CGE models that treat China as a single region to study the potential impact of climate and energy policies (see for example Cao, 2007; Wang et al., 2009; Lin and Jiang, 2011; Dai et al., 2011; Qi et al., 2013). Qi et al. (2013) shows the importance of a CGE framework for assessing the impact of renewable policies in an economy-wide framework, finding that the carbon reductions due to replacing coal with subsidized renewable electricity generation put downward pressure on the coal price and lead to its increased use in other sectors. Importantly, this study does not consider sub-national detail in the electricity system nor does it explicitly characterize wind resource based on historical observations. A new model that disaggregates China at the provincial level, the China Regional Energy Model or C-REM, has been developed by the Tsinghua-MIT China Energy and Climate Project, and has been applied to assess energy cap and CO₂ intensity policies with targets differentiated by province (Zhang et al., 2012; Zhang et al., 2013). In the present study, we augment this model with provincially-differentiated marginal cost curves based on a detailed spatial characterization of China's wind resource.

3. Characterization of China's wind resources

3.1 Re-analysis methodology

Recent wind assessments rely heavily on the method of retrospective analysis, or re-analysis. Building on the diverse collection of data measurements available from satellites, ground monitoring stations and upper-air balloons, re-analysis uses a global circulation model to reconstruct complete wind profiles at sub-degree intervals over the span of decades (Rienecker et al., 2011). These data provide geographic granularity adequate for system-wide analysis and account for multiyear variations in wind patterns.

This assessment uses Modern Era Retrospective-analysis for Research and Applications (MERRA) boundary layer flux data, a thirty-one-year (1979-2009), high temporal resolution (one hour) dataset. It was constructed using the GEOS-5 Atmospheric Data Assimilation System, which consists of the GEOS-5 model and interpolation analysis methods (Gunturu and Schlosser, 2011). Boundary layer similarity theory is used to compute China's offshore and onshore wind speeds, and characterize intermittency. The characterization was made at a variety of hub heights (only 80-meter is printed here), at a 0.5° latitude by 0.67° longitude spatial resolution (approx. 56 km x 61 km at mid-latitudes). This paper uses wind power density (WPD), in lieu of wind speed, as the primary geophysical variable on which to perform analyses, because it is independent of wind turbine characteristics and leads to more informative comparisons.

Wind speeds at elevations relevant for wind turbines are strongly affected by atmospheric boundary layers and surface roughness. Assumptions of these parameters vary by study, but typically do not account for variations in seasons, terrain or stability in the atmosphere. Furthermore, the dataset has a much longer timespan than typical studies (i.e., a single year or

several years), which may capture better interannual variations such as the El Nino/La Nina cycles.

3.2 Results of wind resource assessment

Wind power density was calculated at a hub height of 80 meters, and averaged at each hour across the 31-year dataset to account for interannual variation. Low and high extremes of the wind resource face threshold and curtailment constraints, respectively. A power curve translates a given wind power density into actual electricity generation for a given design and size of turbine, taking into account these cut-offs as well as the non-linear performance of turbine generators. This paper uses power curves from a Sinovel 1.5-MW wind turbine (SL1500/82) for onshore, and a Sinovel 5-MW turbine (SL5000/128) for offshore. At each hour and grid cell in the representative year, expected electricity generation was summed and divided by the theoretical maximum, see figures 2 and 3.

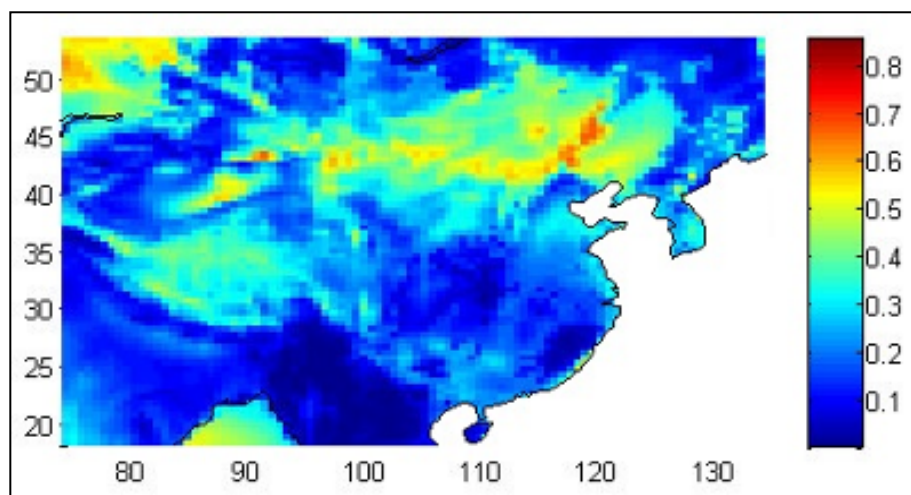


Figure 2. Capacity factors for 1.5-MW onshore turbine. Grid size: 0.5° latitude by 0.67° longitude.

4. Multi-regional computable general equilibrium (CGE) model of China

4.1 Introduction to model

For this study we use the China Regional Energy Model (or C-REM) described in Zhang et al. (2012). In short, the model is a computable general equilibrium model based on optimizing behavior of economic agents. Consumers maximize welfare subject to budget constraints and producers combine intermediate inputs and primary factors at least cost to produce output. Energy resources are primary factors and emissions of carbon dioxide (CO₂) associated with their use are explicitly captured in the model. The model is formulated as a mixed complementarity problem (MCP) and solved using MPSGE (Mathiesen, 1985; Rutherford,

1995). Activity levels and prices satisfy zero-profit and market-clearance conditions.¹

The model describes the production of energy and other goods by nested constant-elasticity-of-substitution (CES) production functions. Inputs into production include labor, capital, natural resources (coal, natural gas, crude oil, and land), and intermediate inputs. For all non-energy goods, the CES production functions are described by the nested structure in Figure 3. The top-level nest combines an aggregate of capital, labor, and energy inputs (KLE) with material inputs (M); the second-level nest combines energy inputs (E) with a value-added composite of capital and labor inputs (VA) in the KLE-nest; the third-level nest captures the substitution possibilities between electricity (ELE) and final-energy inputs (FE) composed, in the fourth-level nest, of coal (COL), natural gas (GAS), gas manufacture and distribution (GDT), crude oil (CRU), and refined oil products (OIL).

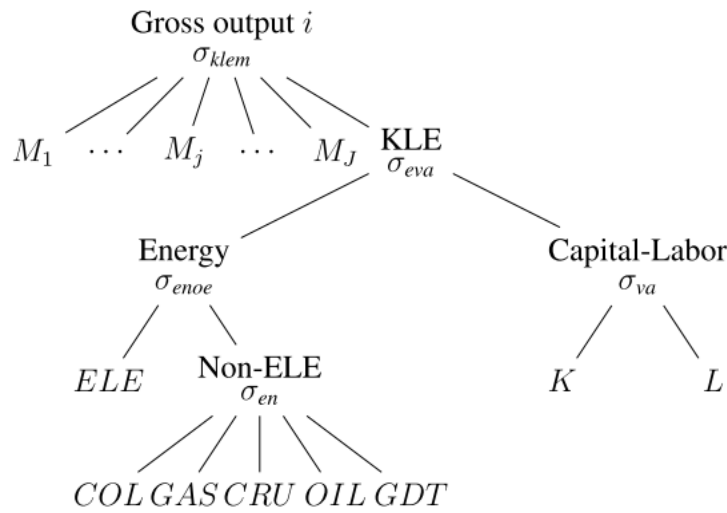


Figure 3. Nesting structure of CES production functions for non-energy goods.

All industries are characterized by constant returns to scale and are traded in perfectly competitive markets. Capital mobility is represented in each sector by following a putty-clay approach in which a fraction of previously installed capital becomes non-malleable in each sector. The rest of the capital remains mobile and can be shifted to other sectors in response to price changes. The modeling of international trade follows Armington's (1969) approach of differentiating goods by country of origin. Goods within a sector and region are represented as a CES aggregate of domestic goods and imported ones with associated transport services. Goods produced within China are assumed to be closer substitutes than goods from international sources to replicate a border effect.

Final consumption in each region is determined by a representative agent who maximizes consumptions subject to its budget constraint. Consumption is represented as a CES aggregate of non-energy goods and energy inputs and the budget constraint is determined by factor and tax incomes with fixed investment and public expenditure.

¹ The model is formulated in the mathematical programming system MPSGE (Rutherford, 1999), a subsystem of GAMS, and solved by using PATH (Dirkse and Ferris, 1995).

4.2 Database and aggregation

The model is built on a comprehensive energy-economic data set which 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 dataset is global, but includes regional detail for China's provinces. The global data (not including China) comes from the database version 8 of the Global Trade Analysis Project (GTAP). The GTAP 8 data set provides 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, and identifies 129 countries and regions and 57 commodities (Narayanan et al., 2012). As we are mainly interested in the sub-national impacts in China, we aggregate the international data to three regions (USA, Europe, and the rest of the world).

The data for China is based on China's national input-output table and the full set of China's provincial input-output tables published in 2007 (National Information Center of China, 2011). The provincial input-output data for China specifies benchmark economic accounts for 30 provinces in China (Tibet is not included due to a lack of data and the small scale of its economic activities). Energy use and emissions data are based on the 2007 China Energy Statistical Yearbook (National Statistics Bureau of China, 2008). The model explicitly represents six energy sectors and 10 non-energy composites.² Zhang et al. (2012) describe in detail the method used for balancing the Chinese data set and merging it with the global dataset. Elasticities of substitution are adopted from the GTAP 8 database, as well as from the MIT Emissions Prediction and Policy Analysis model (Paltsev et al., 2005), in particular for the price elasticities of supply of nuclear and hydro (wind is represented as described below).

4.3 Representation of electricity sector

In the C-REM model the production of energy goods is separated into fossil fuels, oil refining and gas manufacture and distribution, and electricity production. The production of fossil fuels (COL, GAS, CRU) combines sector-specific fossil-fuel resources with a Leontief (fixed-proportion) aggregate of intermediate inputs and a composite of primary factors and energy, described by a Cobb-Douglas function of energy inputs, capital, and labor. Oil refining (OIL) and gas manufacture and distribution (GDT) are described similarly to the production of other goods, but with a first-level Cobb-Douglas nest combining the associated fossil-fuel inputs (crude oil for oil refining; and coal, crude oil, and natural gas for gas manufacture and distribution) with material inputs and the capital-labor-energy (KLE) nest. Electricity production is described by a Leontief nest which combines, in fixed proportions, several generation technologies, including nuclear, hydro, and wind power, as well as conventional power generation based on fossil fuels. Non-fossil-fuel generation is described by a CES nest combining specific resources and a capital-labor aggregate.

To model spatial variability of wind, this paper takes the general approach of Paltsev et al. (2005) of adding a "resource cost" to the wind power production tree, reflecting resource data on usable wind electricity generation, with an initial value share of 0.2. Each province has a unique

² The energy goods include coal (COL), crude oil (CRU), refined-oil products (OIL), natural gas (GAS), gas manufacture and distribution (GDT), and electricity (ELE); the non-energy sectors include agriculture (AGR), minerals mining (OMN), light industries (LID), energy-intensive industries (EID), transport equipment (TME), other manufacturing industries (OID), water (WTR), trade (TRD), transport (TRP), other service industry (OTH).

wind resource supply curve based on its wind resources characterized in Section 3.2. The increasing marginal cost of wind deployment within a region corresponds to decreasing marginal capacity factor as preferred wind resources are consumed.

4.4 Calculating wind cost production curves

Using the detailed grid-cell data on capacity factors, the marginal cost of wind is represented as a function of expanding generation to exploit less favourable resources. To develop wind supply curves by province, information on wind availability from the above analysis is combined with information about geographical constraints on usable land area for turbine construction. The production cost is calculated using the common metric, levelized-cost-of-electricity (LCOE), that represents the cost of the electricity generated over the life of the turbine. The following two sections describe how this information is integrated to yield an assessment of the cost of wind generation expansion by province.

4.4.1 Wind electricity cost model

We employ a standard calculation for the LCOE of wind electricity, which is performed for every grid point using its unique capacity factor generated from the above wind resource analysis. Table 3 describes the cost model assumptions.

Model input	Present analysis
Debt-equity ratio	80/20
Rate of return	10%
Capital cost	15 mil RMB per 1.5MW turbine (12000 for the equipment cost and 3000 for other cost)
Operations and maintenance costs	100 RMB / MWh
Tax	VAT (8.5%) + EIT (0%, $t \leq 3$; 12.5%, $3 < t \leq 6$; 25%, $t > 6$) VAT plus VAT surcharge is applied on equipment
Loan	Interest rate = 6.2% over 15 year term, payment starting from year 3
Depreciation starting year	4

Table 3. Key assumptions used in wind cost model.

The cost calculation is based on a Sinovel 1.5-MW wind turbine that has an equipment cost of 12 million RMB and 3 million for other costs, including land rental, permitting services, and other one-time costs. This results in a relatively higher LCOE than McElroy et al. (2009), which assumes a cost of 12.5 million. As in other studies, we assume a 80/20 debt-to-equity ratio and a required rate of return of 10%. Operations and maintenance (O&M) costs are assumed to be 0.1 RMB per kWh generated. This study assumes loan payments start in year 3 (the year after loans are taken out) and that depreciation on the project equity starts from year 4. These assumptions have very little impact on the overall cost.

4.4.2 Physical constraints

Urban areas, slopes greater than 10% and geographic features such as lakes, rivers and major industrial and transportation facilities should not be considered for siting. An exclusion map of unavailable locations for wind turbines was constructed in the ArcGIS platform using 30-arcsecond elevation data from NASA's Shuttle Radar Topography Mission and a land-cover classification for China from satellite remote-sensing (USGS, 2004; Liu et al., 2003). Figure 4 indicates areas available (in white) for onshore turbine construction. For offshore turbines, areas within 100km of the coast and at depths shallower than 100 meters were taken as suitable for construction. This analysis did not account for offshore exclusion zones such as areas used for shipping or fishing.

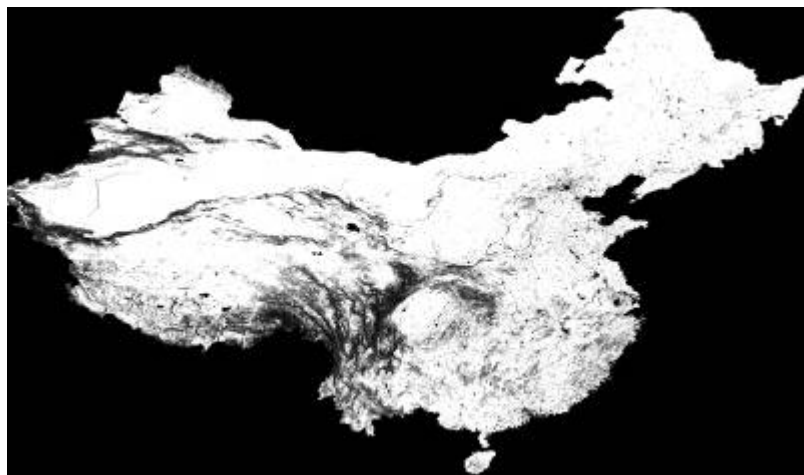


Figure 4. Available areas (white) for onshore wind turbine construction. Grid size: 30-arcsecond ($\sim 1\text{km}^2$ at mid-latitudes).

Assumptions about optimal turbine spacing also significantly affect the total estimated wind generation. Much research has been devoted to determining the maximum density of wind turbines allowable in a farm before the effective power of downstream turbines is reduced. Rules of thumb such as 3-5 rotor diameter spacing cross-wind and 5-9 diameter spacing upwind have historically been used (Masters, 2004). Recent studies, however, have reopened the debate and indicated the need to consider additional effects to explain experimentally observed power fall-off at turbine spacings of 7 and 10 rotor diameters (Hirth & Schroeder, 2012).

This paper uses the results of Meyers & Meneveau (2012) in characterizing surface roughness effects of large wind farms on the atmospheric boundary layer. They conclude that the commonly used spacing of 7 rotor diameters by wind developers may be suboptimal, and recommend a turbine spacing of around 15. With this spacing, a single 1.5-MW turbine with an 82-meter rotor diameter occupies 1.38 square kilometers. Taken together, the land availability, turbine spacing, and LCOE information are used to construct that wind cost curves described in the following section.

4.4.3 Results of wind production costs

Figures 5, 6 and 7 show the cost curves for wind electricity nationally, in select provinces, and offshore, respectively, each fitted to power curves for later analysis.

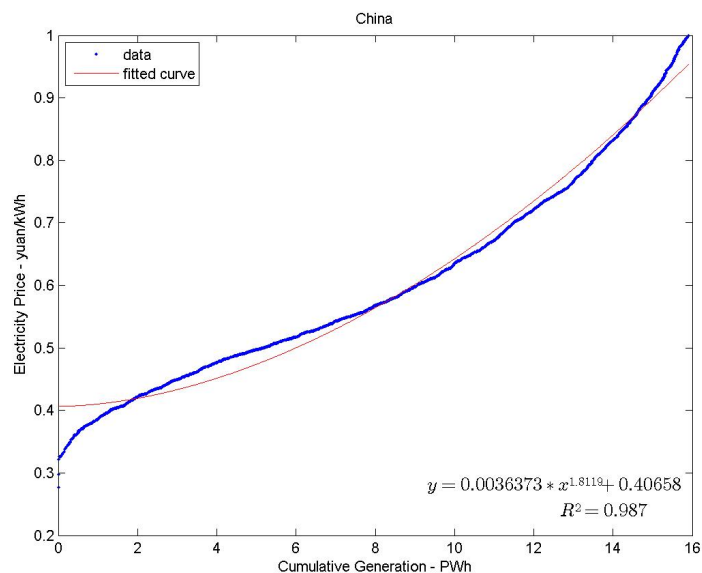


Figure 5. National wind production cost curve (onshore only). (RMB / kWh vs. PWh)

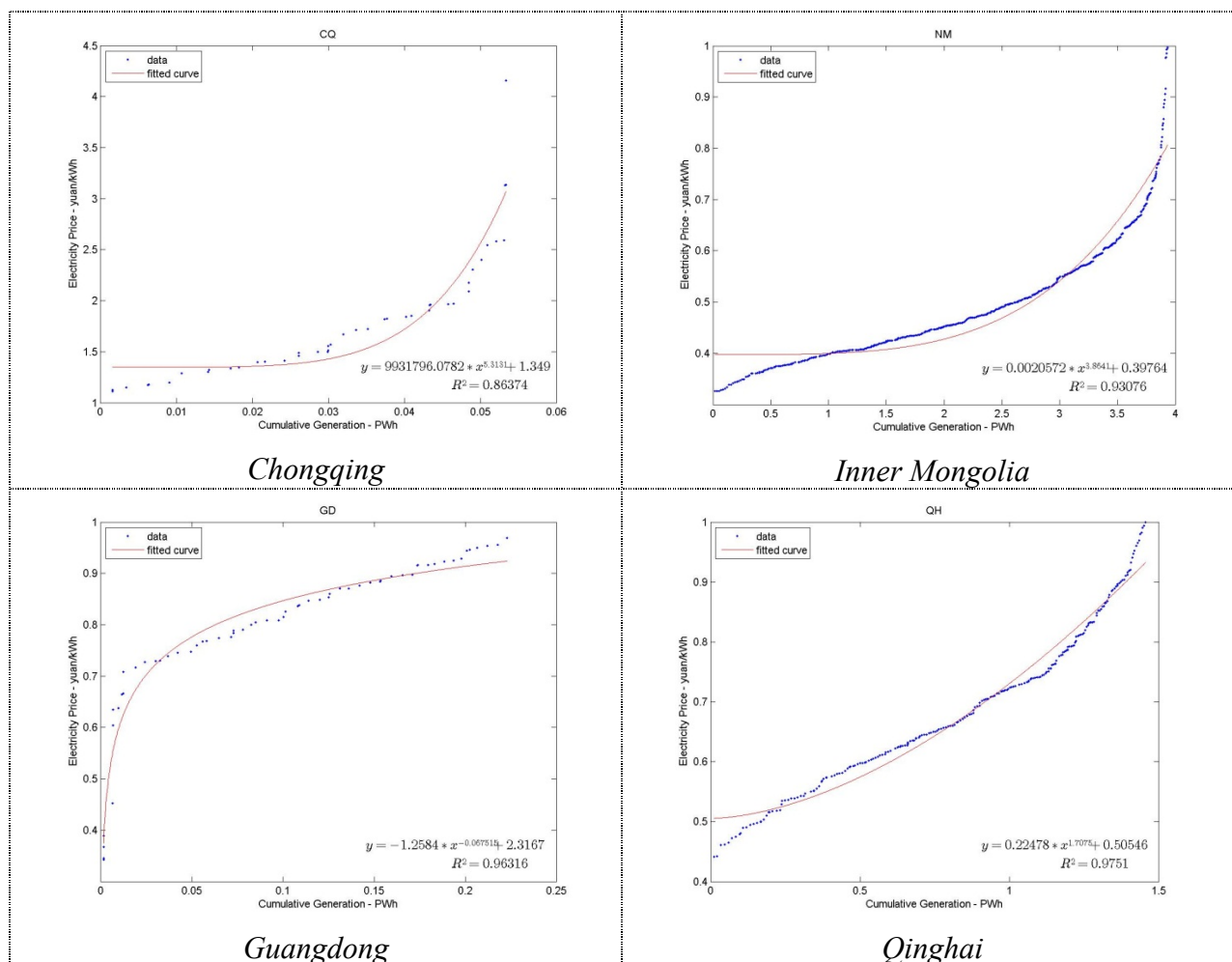


Figure 6. Select provincial wind production cost curves (RMB / kWh vs. PWh)

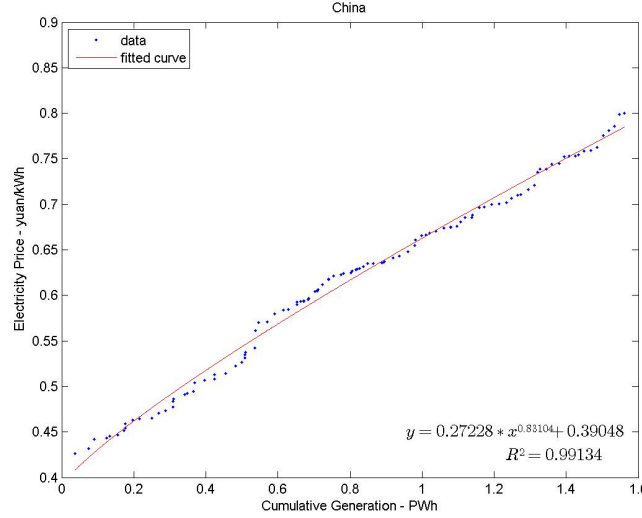


Figure 7. Offshore wind production cost curves. (RMB / kWh vs. PWh)

In Figure 6, the supply curves illustrate the extremes of wind resource availability within provincial borders. From least to most abundant: Chongqing, Guandong, Qinghai, Inner Mongolia. The offshore region in Figure 7 was taken to be the area within 100km of the coast and at depths of less than 100m.

4.5 Representing wind resource and cost detail in the C-REM model

4.5.1 Elasticity of substitution

We introduce wind cost into a “top-down” representation of the electricity sector in each of China’s provinces. We discuss here how we model wind as a “backstop” technology using a CES function and discuss special treatment for individual provinces in Section 4.5.2 below. In the CES formulation the electricity sector is modeled as a representative firm that minimizes production costs subject to technological, market, and resource constraints, which are defined by its associated CES function. The contribution from wind generation at time t in region r is given by (the zero-profit condition):

$$p_{t,r} \geq \left\{ \theta_r (\mu_r \cdot p_{w,t,r})^{1-\sigma_r} + (1 - \theta_r) (\mu_r \cdot p_{k,t,r})^{1-\sigma_r} \right\}^{1/(1-\sigma_r)}$$

$p_{t,r}$ is the price of wind electricity output and is treated as a fungible commodity with other electricity types. θ_r is the cost share of the wind resource by province, while $p_{w,t,r}$ is the variable wind resource price. σ_r is a region-specific elasticity of substitution between the wind-resource and other inputs, in this case capital, denoted by k . μ_r is a markup factor defined by the ratio of the marginal cost of the first kWh of delivered wind electricity and the base-year marginal cost of the benchmark electricity generation technology. In reality, new generation technologies scale up gradually even when the economics are favorable. To replicate this behavior in the model, we parameterize a technology-specific fixed factor that expands as a function of production in the

previous period but remains constrained by its value and the ability to substitute between it and other inputs, which is defined by σ_r above.

The detailed provincial-level wind cost information enters the model through σ_r , which is calibrated by fitting a power function to the LCOE supply curves derived above. First, the price elasticity of supply is estimated using the relation:

$$\ln(q_{r,k}) = \alpha + \epsilon_r \log(LCOE_{r,k}) + \epsilon_{r,k}$$

where k is a wind site located within region r , $q_{r,k}$ is the electricity output, and ϵ_r is the price elasticity of wind power supply by province. α is a constant and $\epsilon_{r,k}$ is the regression error term. The elasticity of substitution by province that characterizes the relationship between resource factor and other inputs:

$$\sigma_r = \frac{\epsilon_r}{1 - \theta_r}$$

This substitution elasticity σ_r is incorporated into the CES nest representing wind generation technology for every province in China. With heterogeneity in wind resource availability and cost represented in the model, we can forecast baseline generation and the impacts of policy. The following section considers a simulation of a feed-in tariff for wind electricity generation.

4.5.2 Backstop technology criteria

Wind is formulated as a backstop technology in our CGE model. This is typically used for new technologies that should be turned on or off depending on policy or other constraints, such as technology availability. For simplicity, the wind backstop technologies only use two inputs, capital and wind resource. The initial value share of the wind resource was set to 0.2.

The criteria used to formulate the backstop were two-fold: the cost of the wind resource relative to market rates and the prevailing FIT in the province, and a cap on wind penetration in each province of 20% of generation. The latter is used as a proxy for issues of grid integration discussed in Section 1.2, and was chosen in a reasonable range of current and projected curtailment rates. One study on China found that a national penetration of 26% was the cutoff above which integration costs become limiting (Liu et al., 2011). Other systems, such as Texas, see curtailment issues (though less severe than in China) at much lower penetrations rates, 8-9%. Since we expect, in the long-run, additional transmission capacity and loads closer to wind to be built to alleviate some of the current congestion, an intermediate value was chosen for the maximum penetration allowed: 20%. Further study based on detailed power systems models is needed to improve this approximation.

Feed-in tariffs for each province as shown in Figure 1, a default market price of 0.5 RMB / kWh, and the cost curves in Section 4.4.3 were used to categorize the wind representation in the CGE. For provinces with multiple FITs, the lowest was used. The criteria for the wind backstop technology by province were chosen as follows:

- (1) We consider separately provinces that have wind potentials under the market price of at least

20% of total annual generation: Gansu, Hebei, Heilongjiang, Jilin, Liaoning, Neimenggu, Qinghai, Shanxi and Xinjiang. For those provinces, we model a Leontief backstop technology ($\sigma_r = 0$) that represents wind potential below the market price, and the 20% cap becomes binding.

- (2) For provinces that have wind potentials under the market price but less than 20% of total annual generation, we further differentiate:
 - a) Provinces that above the market price have only one cost level of potential wind resource below the feed-in-tariff, which corresponds to a single grid cell that is cost competitive only with subsidy (supply elasticity is infinite): Guangdong, Hainan, Shanghai, and Zhejiang. We will model one Leontief backstop technology which represents the wind potentials below the market price and another Leontief backstop technology that represents the wind potentials between the market price and feed-in-tariff and receives the feed-in-tariff.
 - b) Provinces that have several cost levels of wind potentials between the market price and feed-in-tariff (supply elasticity is a positive number): Fujian and Shandong. We will model one Leontief backstop technology which represents the wind potentials below the market price and another CES backstop technology represents the wind potentials between the market price and feed-in-tariff. The elasticity of substitution between capital and wind resource σ is calculated following the methods described in Rausch et al. (2012) (and discussed in the previous section). The CES backstop technology will receive feed-in-tariffs.
- (3) Provinces that have no wind potential below the market price but have wind potentials below the feed-in-tariff level. We further differentiate:
 - a) Provinces that only have one cost level of wind potentials between the market price and feed-in-tariff, which corresponds to a single grid cell that is cost competitive with subsidy (supply elasticity is infinite): Beijing, Ningxia and Tianjin. We will model one Leontief backstop technology that represents the wind potentials between the market price and feed-in-tariff and receives feed-in-tariffs.
 - b) Provinces that have several cost levels of wind potentials between the market price and feed-in-tariff (supply elasticity is a positive number): Jiangsu, Shaanxi and Sichuan. We will model one CES backstop technology that represents the wind potentials between the market price and feed-in-tariff.
- (4) Provinces that do not have any wind potential below the feed-in-tariff level: Anhui, Chongqing, Guangxi, Guizhou, Henan, Hubei, Hunan, Jiangxi and Yunnan. The backstop technology for wind will not be turned on in the model.

A detailed description of threshold values used to characterize the wind resource availability at the provincial level along with its relationship to wind costs and the impact of a feed-in tariff are shown in Table 4.

Province	(1) 20% of annual generation (TWh)	(2) Wind potentials below market price (TWh)	(3) The lowest cost below FIT (RMB/kWh)*	(4) Wind potentials at this lowest cost (TWh)	(5) Elasticity of supply for wind potentials between market price and feed-in-tariff**
Anhui	17.36	0	N/A		
Beijing	4.54	0	0.55	2.3	infinite
Chongqing	7.32	0	N/A		
Fujian	20.78	2.5	0.51	3.5	1.1
Gansu	12.4	160	/		
Guangdong	53.9	6.5	0.6	0.4	infinite
Guangxi	13.7	0.5	N/A		
Guizhou	22.76	0	N/A		
Hainan	2.28	0.1	0.55	1.9	infinite
Hebei	32.92	124	/		
Henan	37.28	0	N/A		
Heilongjiang	13.98	95	/		
Hubei	30.82	0	N/A		
Hunan	16.74	0	N/A		
Inner Mongolia	36.6	2620	/		
Jilin	10.02	330	/		
Jiangsu	56.5	0	0.57	1.6	1.1
Jiangxi	9.88	0	N/A		
Liaoning	22.26	270	/		
Ningxia	9.06	0	0.57	1.9	infinite
Qinghai	6.04	170	/		
Shaanxi	12.9	0	0.54	1.1	0.59
Shandong	51.92	1.4	0.53	6.1	0.49
Shanghai	14.84	0.04	0.57	3.2	infinite
Shanxi	35.18	35	/		
Sichuan	24.52	0	0.51	7.4	4.1
Tianjin	7.98	0	0.6	1.3	infinite
Xinjiang	8.4	718	/		
Zhejiang	41.6	0.03	0.59	0.1	infinite

Table 4. Threshold values of wind resources by province used in CGE model. A market price of 0.5 RMB / kWh was used for all provinces.

* Only for those provinces that have wind potentials under the market price less than 20% of total annual generation.

** “infinite” here means this province has only one grid cell with wind potential between the market price and the FIT.

5. CGE modeling results

The feed-in tariff for wind is the primary policy instrument China has used to expand wind electricity since its establishment in 2009. We apply C-REM with detailed wind characterization by province to assess the impact of a feed-in tariff on future wind electricity generation in China. We simulate the optimal economic contribution of wind to the electricity generation mix by province.

5.1 Wind generation by province

The provincial results of wind generation are in Table 5. We find that nationwide wind electricity generation is approximately 213 TWh. The majority (84%) of this comes from provinces with significant wind resources that are already cost-competitive using the above assumptions, such as Inner Mongolia with 37 TWh, Shanxi with 35 TWh, Liaoning with 22 TWh, and Hebei with 33 TWh. We suggest that the national total be interpreted with caution, mindful of the modeling assumption employed, namely a cap on 20% of generation from wind at the provincial level. Therefore, though Xinjiang has a rich, cost-competitive wind resource potential (718 TWh), it is assumed that only 20% of Xinjiang's total load can be met by wind, 8.54 TWh.

<i>Province</i>	<i>Generation (TWh)</i>	<i>Province</i>	<i>Generation (TWh)</i>
<i>Provinces with >20% below market price (20% cap is binding)</i>		<i>Provinces with no wind below market price</i>	
Gansu	12.40	Fujian	6.11
Hebei	32.92	Jiangsu	2.01
Heilongjiang	13.98	Ningxia	1.67
Inner Mongolia	36.60	Shaanxi	1.23
Jilin	10.02	Sichuan	8.56
Liaoning	22.26	Tianjin	1.09
Qinghai	6.04	<i>Provinces with no wind under CGE model</i>	
Shanxi	35.18	Anhui	-
Xinjiang	8.40	Chongqing	-
<i>Provinces with >0% and <20% below market price</i>		Guangxi	-
Guangdong	6.83	Guizhou	-
Hainan	1.83	Henan	-
Shandong	2.96	Hubei	-
Shanghai	2.86	Hunan	-
Zhejiang	0.12	Jiangxi	-
		Yunnan	-
		China	213.06

Table 5. Long-run contribution of wind to provincial electricity generation with the feed-in tariff.

Additionally, we find some provinces with wind resources that are only cost-competitive under a FIT scheme, namely: Fujian, Jiangsu, Ningxia, Shaanxi, Sichuan and Tianjin.

Intermediate provinces – where some wind is below the market price, but additional wind can be supported under a FIT – include: Guangdong, Hainan, Shandong, Shanghai, and Zhejiang.

5.2 CO₂ emissions reductions

An important goal of installing renewable energy is the reduction of CO₂ and CO₂ intensity of economic activity. We find that the total nationwide CO₂ reduction from wind generation is 3.5%. While this number is relatively modest, it is consistent with the relatively low or nonexistent contribution of wind to generation in most provinces. Impacts on CO₂ and energy intensity are similarly modest: we find that energy intensity falls by 3.4% and CO₂ intensity falls by 3.7%, consistent with the fact that adding wind delivers essentially carbon-free energy.

6. Conclusions

This paper has demonstrated how detailed scientific characterization of the onshore wind resource for China can be incorporated into a provincially-disaggregated model and used to assess the impact of policy options for promoting renewable electricity expansion. The main methodological contribution of this paper is to demonstrate a first step toward how detailed scientific information can be used to differentiate wind resource by location and quality, which can then be represented within a CGE framework. We apply this framework to investigate the impact of a FIT in China, which is an important contemporary policy question.

6.1 Preliminary implications for policy

This analysis provides an important platform that, with appropriate refinements, can contribute to several important policy questions. We find that China's wind resources are concentrated in a handful of provinces, which assuming generous penetration rates and limited interconnection, leads to significantly less abundant national wind electricity potential than other studies (domestic and international), and less than current Chinese government targets. By 2020, China aims to generate 390 TWh from wind, whereas this analysis yielded only 213 TWh at current FIT levels. At this quantity – which is roughly twice wind generation in 2012 – carbon reductions of 3.5% could be observed.

Additionally, the FIT policy we investigate here does not play a key role in deploying wind in several provinces, and in others no wind is constructed at all. This suggests that additional parameters such as costs of curtailment and the operational benefits of transmission interconnection need to be investigated in more detail, and this will require new methods of incorporating engineering and resource data into a CGE framework. This future research will help to identify robust decision strategies for generation and transmission expansion planning.

On the other hand, the FIT is shown to have a critical role in deploying wind in provinces that have significant loads and moderate wind resources. These provinces – such as Sichuan, Fujian and Jiangsu – are good locations from the perspective of reducing the impacts of intermittency as they have large loads and do not require expensive transmission investments to integrate wind. Additionally, Fujian and Sichuan have large hydropower capacities, which is an ideal load-balancing technology. Because of this, Fujian is one of the few provinces that saw no curtailment of wind last year (Lin, 2012).

A FIT delivers a modest reduction in CO₂ emissions, in part because it is a supply-side policy focused on a single sector. It has no effect on the large contributions to CO₂ emissions from the transportation and energy-intensive industrial sectors, nor does it directly discourage the use of other CO₂ intensive electricity sources. A CGE framework has the advantage of capturing the impact of the FIT on the allocation of resources within the broader economy, which is essential when considering environmental problems tied to commodities such as fossil fuels or electricity, which are inputs to a broad set of diverse economic sectors.

6.2 Caveats and future work

We recognize that the modeling framework presented makes several strong assumptions that, despite efforts to capture realism in resource availability and the cost of wind electricity development, may lead to a misestimation of economically-viable resource. These influences can be divided into static and dynamic factors, and represent the richness of possibilities for future work in this area.

Static factors are those that affect the equilibrium amount of wind electricity in a static CGE model such as the one presented (a snapshot of the economy in equilibrium). These include:

- 1) **Intermittency.** Wind generation is not a perfect substitute for fossil-fuel generation because of its intermittent character. Given the existing generation mix, there is an upper limit of wind introduction to the grid if there is no back-up capacity for wind (which will increase the cost of wind significantly and will be left for future study). Here we set this upper limit as 20% of total annual generation by province, though other assumptions can be made.
- 2) **Curtailment.** Related to intermittency, this is the foregone revenue to wind generators when grid operators choose to spill wind generation without compensation for grid stability and other reasons. As this was roughly 17% of all usable wind generation last year, this has a large impact on the financial performance of wind projects.
- 3) **Grid-connection.** Wind farms typically require some additional transmission infrastructure to reach a substation, from several kilometers or longer. These costs are highly location-specific and the cost allocation does not follow transparent guidelines. As wind farms may be non-operational for the first year or more waiting to be connected, this also represents an opportunity cost for developers.
- 4) **Limited inter-provincial electricity transfers.** Wind resources can contribute to electricity supply across provincial borders, but significant challenges exist to strengthening regional interconnections in the Chinese power sector. This model does not allow for these transfers, which if incorporated would reduce the cost of generating wind power by relaxing the 20% binding cap on wind penetration, especially in wind-rich provinces.

These results do not match up with historical wind installation, and there is reason to believe that a static model, representing a single snapshot in time, cannot reproduce exactly the quantities and prices in an economy. To understand better the limits to wind power growth, certain dynamic factors should be considered for future work:

- 1) **Financing.** Capital is required to build new installations for wind. However, in reality, a fraction of previously-installed capital becomes non-malleable in each sector of the economy

and even higher for electricity sector in the short term, roughly 5-10 years. In our scenario – which reflects the long-term wind development – no vintaging of the capital stock is modeled.

- 2) **Project approval.** The central government is trying to control the rapid growth rate of wind, because of the decreasing capacity factors observed and poor connection rates. As of 2011, all new wind power projects must be approved by the National Energy Administration to qualify for the FIT, which may have a dampening effect on installations (NEA, 2011).
- 3) **Production capacity.** In reality, new generation technologies scale up gradually even when the economics are favorable. To replicate this behavior in a dynamic model, a technology-specific “fixed factor” is included as an input to production that expands according to production in the previous period.

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