



POTSDAM-INSTITUT FÜR
KLIMAFOLGENFORSCHUNG

Originally published as:

Zhang, S., Bauer, N., Luderer, G., Kriegler, E. (2014): Role of technologies in energy-related CO₂ mitigation in China within a climate-protection world: A scenarios analysis using REMIND. - Applied Energy, 115, 445-455

DOI: [10.1016/j.apenergy.2013.10.039](https://doi.org/10.1016/j.apenergy.2013.10.039)

Available at <http://www.sciencedirect.com>

© Elsevier

Role of technologies in energy-related CO₂ mitigation in China within a climate-protection world: A scenarios analysis using REMIND

Shuwei Zhang*, Nico Bauer, Gunnar Luderer, Elmar Kriegler

Potsdam Institute for Climate Impact Research, Telegrafenberg A31, 14473 Potsdam, Germany

H I G H L I G H T S

- The augmented REMIND model is used to study the role of energy technologies under a carbon tax.
 - The scale and timing of fossil fuels with CCS, nuclear, and renewables are examined.
 - CCS is important but the window of opportunity for its deployment is limited.
 - The effectiveness of nuclear is strongly linked to its cost performance.
 - Renewable energy is a long-term mitigation option.
-

A B S T R A C T

In a world with the need of climate protection through emission reduction, China's domestic mitigation will be put on the national agenda. The large-scale deployment of innovative technologies induced by climate policies is a key determinant for reducing emissions in an effective and efficient manner. A distinguishing feature of the Chinese energy sector (especially electricity generation), is that investment costs are significantly lower than in other world regions. Represented in the methodological framework of the augmented REMIND model, three promising mitigation technologies (also known as technology clusters) in the electricity sector: CCS with advanced coal-generation technologies, nuclear, and renewables are the focus of this study. The scenarios are designed to analyze the roles of these technologies and their associated economic impacts under a climate policy (i.e., a carbon tax). Our results indicate that:

- (1) Technology policies improving the techno-economic features of low-carbon technologies are insufficient to restrain China's increasing emissions.
 - (2) Carbon-pricing policies can effectively reduce emissions by making low-carbon options more competitive than conventional fossil fuel alternatives. In the global carbon tax regime framed in this paper, China's mitigation potential is larger than that of any of other region and the peak of emissions occurs earlier (by 2020) and is 50% lower than in the BASE scenario.
 - (3) CCS is important, but the window of opportunity for its deployment is limited to the near- to mid-term future. It is important to lower the cost of the carbon tax by supplying CCS technology; however, the gains from CCS for the "myopic" fossil fuel sectors are limited, compared to the case without CCS. Therefore, strong social support for CCS development should be implemented, if it is to be an effective mitigation option.
 - (4) The cost of nuclear is a major determinant of the future development pattern in China's power sector. Renewables are the long-term solution (with large-scale deployment only after 2030, solar PV in particular) for deep emissions mitigation. The creative policies reflected by alternative investment, technology innovation, and climate protection strategies should be explored and implemented to make use of their long-term potential.
-

1. Introduction

Anthropogenic climate change is a global problem of unprecedented scale [1]. China and other developing countries involved in the Bali roadmap have agreed to take appropriate mitigation ac-

tions at the national level. This commitment demonstrates that no matter what climate policy regime is instituted by the international community in the coming years, China's mitigation strategy will be put on the domestic agenda [2]. Furthermore, the Durban Platform comprises a protocol signed by countries including China, which states that they are going to take steps to negotiate a new climate treaty by 2015, wherein a legally binding commitment including all parties is expected to enter into force in 2020.

Integrating mitigation policies into national, social, and economic policies and relying on innovative science and technology are the pillars of China's climate change mitigation strategy [3]. Technological advancement is a major concern in China and will play a crucial role in the process of transforming the Chinese energy sector towards a low-carbon pathway. An analysis of the global context is of particular interest because investment costs for technology innovation in China are generally lower than in the rest of the world (particularly OECD countries) [4,5]. This observation applies to conventional coal-fired power plants as well as domestically manufactured nuclear, wind turbines, and solar PV panels. The effectiveness of carbon taxes to reduce emissions depends crucially on the investment costs of alternative technologies and their relative contributions to the energy supply. Although it is possible to analyze the cost of electricity at the plant level, analyzing the system-wide effects of carbon taxes requires a comprehensive model that represents China and the rest of the world. This study uses REMIND¹ [8,9] for this purpose.

The nexus between technology dynamics, the effectiveness of carbon taxes, and the associated costs of climate change mitigation are the central research topics of this paper. We address three questions: (1) what are we heading if focusing on technology performance rather than directly addressing emissions in China's climate policies ("baseline" uncertainty)? (2) How are different technologies and their performances related to their roles in the energy (power) sector and the emissions time path? (3) What are the key technologies and how do their characteristics affect the scale, timing, and associated costs of reducing emissions?

This study uses REMIND, a long-term, global, multi-regional model. Furthermore, it focuses on three technology clusters: (1) CCS (carbon capture and sequestration) with advanced coal generation (super-critical and IGCC, integrated gasification combined cycle) technologies, (2) nuclear, and (3) renewables (wind and solar PV). These technologies, all in the power sector, are commonly regarded as China's primary mitigation options, both in the short- and long-term.

These technologies have been reviewed and studied from the economic perspective before in an separated manner (e.g. [10] for CCS, [11,12], for renewable, and [13] for nuclear), or in a systematic modeling manner (e.g. [14,15] with Integrated Assessment Models, [16–18] with economic or economic-technology hybrid models, and [19–21] with bottom-up models, and other micro-models, e.g. [22,23]). However, each technology cluster is now changed with new attributes, e.g. subject to various uncertainty: CCS technology is still in the pilot stage, and its application is controversial in terms of the energy loss, potential damage to environmental integrity, and safety if put into real operation [24–26]; The integration of renewables into the power grid is critical, as now China suffers from the curtailment of electricity from renewables, and the cost of integration is a major concern [27]. Finally, nuclear will likely become more expensive globally due to stricter safety standards after the nuclear accident in Fukushima, Japan. All of

these need to be re-assessed from the perspective of mitigation contribution of various technologies in China. This study aims to contribute to the existing literature, via systematically analyzing technology and China's role in climate change mitigation by examining climate policy responses and the economic uncertainties related to low-carbon technologies, within an economic-efficient world, and explicitly considering the interaction between China and the rest of world.

The scenarios are constructed to consider these issues specifically. The climate policies in this study are implemented via a global carbon tax on the energy sector's CO₂ emissions, which will be implemented after 2020 with an increasing trend over time. The scenarios' time horizon covers the entire 21st century, but our findings are mainly focused on the period leading up to 2050.

The remainder of this paper proceeds as follows: Section 2 introduces the REMIND model and its extension, as well as the technological heterogeneity across world regions. Section 3 describes the scenarios' design and how they are related to the research questions. Section 4 outlines the roles of the technologies in providing energy services and mitigation, as well as the impacts of their performances on the economic costs of mitigation. Finally, Section 5 presents conclusions and policy implications for technology development and climate change mitigation in China.

2. Analytic framework

2.1. REMIND model

REMIND incorporates the economy, the climate system, and a detailed representation of the energy sector. The resulting CO₂-emissions path minimizes mitigation costs for the world economy by fully exploring the when- and where-flexibility of mitigation measures, given the full tradability of emissions permits and the inter-temporal equilibrium of the international capital market. A substantial number of energy technologies (about 50) is available in the energy sector module for the conversion of primary energies to secondary energy carriers.

GDP (Gross Domestic Product) and population growth are two major driving forces for most of economic models, as well as for REMIND. As shown in Fig. 1, a region's GDP is determined by a nested production function with constant elasticity of substitution (CES). Inputs at the upper level of the production function are labor, capital, and final energy. Labor is provided by the population at working age, which comes from UN population data 2010 (http://esa.un.org/wpp/unpp/panel_population.htm). An efficiency parameter is assigned to each production factor in the various macro-economic CES functions to finally determine the GDP trajectory.

Carbon taxes are the climate policy applied in this study, so it is worthwhile to illustrate the mechanism of carbon tax in the model formulation. The tax is implemented as a penalty on emissions, i.e. an incremental cost using the energy. The tax expenditure as part of each region's budget constraint is recycled in a lump-sum manner. The model is solved iteratively with adjusted tax revenues until these match the tax payments.

REMIND allows for the analysis of technology options and policy proposals for climate mitigation. The model and its results are widely presented in economic journals, as well as the interdisciplinary and policy journals (see <http://www.pik-potsdam.de/research/sustainable-solutions/models/remind> for details). For detailed model descriptions and formulations, please refer to Leimbach [28] and Bauer et al. [29].

¹ It should be noted that the model we use, REMIND is an integrated assessment model (IAM) developed at Potsdam Institute for Climate Impact Research (PIK), and is a central tool for energy and climate policy assessment, which is irrelevant to another model REMIND with similar name, but used to ease optimizations of resource usage in factories/production lines (<http://code.google.com/p/tremind/>), e.g. at [6,7].

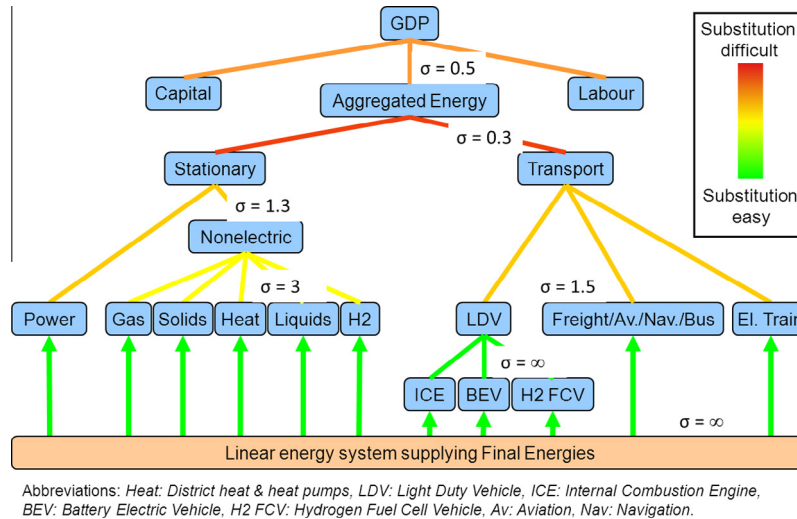


Fig. 1. CES production function and linking with energy system in REMIND.

Table 1
Techno-economic parameters of regions with the lowest technology investment costs.

	Life time	Initial investment cost (2005\$/kW)	Region with lowest investment cost	Source and remarks	Rate for learning technology (2005\$/kW)
PCC	40	610	China	IEA (2010) [4], P48	–
PCC + CCS	40	1710	–	Commercial-grade CCS unavailable; therefore, incremental cost of 1100 \$/kW of CCS is applied to the original technology using the post-combustion, Data from Bauer (2005) [30]. The capture rate is 90%.	–
PC plus oxyfuel	40	935	China	Oxyfuel combustion. The carbon capture rate is 99%.	–
IGCC	40	1500	China	Jiao (2007) [31]	–
IGCC + CCS	40	1900	–	400 \$/kW of CCS applied to the original technology, assuming syngas is used for CCS, updated from Bauer (2005) [30]	–
Nuclear	40	2100	China	IEA (2010) [4]	–
Wind	25	1200	India	IRENA (2012) [5], middle estimation based on the cost range in P30, Fig. 4.9.	12%
Solar PV	30	3000	China	IRENA (2012) [5]. P23, Fig. 4.6.	20%

Note: All of the money value are real \$ in 2005 after inflation adjustment.

2.2. Representation of technologies

2.2.1. Energy and technology in the model

In REMIND, electricity is considered an input for stationary energy use and transport services, which is aggregated with other final energy inputs. The aggregate of all final energy inputs is combined with macro-economic capital and labor to generate GDP in the macro-economic production function (Fig. 1).

Energy supply is represented by the energy sector, which is comprised of the production and conversion processes from primary energy to secondary energy, and secondary energy to final energy, which are then linked with the bottom level of the CES function.

2.2.2. Heterogeneous investment costs across regions

The model used in this analysis is an augmented version of ReMIND, where—to reflect the heterogeneous technology attributes—regionally specific investment costs were introduced to reflect the heterogeneity of regions (Appendix A). This is determined by the authors' estimation based on various sources, mainly IEA (2010) [4] and IRENA (2012) [5]. The investment costs of the technologies in the region with the lowest investment costs are illustrated in Table 1. Using this region as a reference, the techno-economic parameters for the other regions are set by introducing

the appropriate adjustment factors. The adjustment principle (i.e., the setting of this factor for some regions with insufficient data), is detailed in Appendix A. Using this differentiation, every region is characterized by specific cost dynamics to reflect the heterogeneity across the regions, even in the long-term.²

3. Scenario design

Our scenarios cover two dimensions: technology and carbon policy. The research questions above suggest a comparison between two sets of scenarios: with a carbon tax and without a carbon tax. We use the same carbon tax trajectory for the different technology cases, which allows us to analyze the emissions reductions achieved in the different technologies at the same marginal abatement costs. It also allows us to analyze the macro-economic impacts of this tax under different technology settings. The selection of “carbon tax”, rather than other command-and-control measures (e.g. Technology mandates), or emission cap (e.g. burden sharing regime) etc. as the mitigation policy in the paper, is some simplified treatment, to avoid complex discussion that are beyond the topics of the paper. That is, the objective of this study is to ana-

² The alternative augment on the model, e.g. introducing technology spillover on part of the investment cost is an on-going work, and will not be included in this paper.

Table 2
Overview of scenarios.

	Without climate policy (BASE)	With climate policy (POL)
Pessimistic development (P)	BASE-P	POL-P
Reference	BASE	POL
Optimistic development (O)	BASE-O	POL-O
Optimistic key technology scenarios (T)	BASE-T	POL-T

lyze the differential impact of technology availability and performance in China.³

Within the technology dimension, we vary the assumptions regarding the availability and performance of key low-carbon technology options in China, while keeping the assumptions in other regions constant. Since these technologies diffuse into the energy sector regardless of if there is a carbon tax, variations along this dimension will affect both the policy and baseline scenarios. [Table 2](#) illustrates the setup of the scenario used in this study.

In the technology dimension, the uncertainties related to CCS, low or high integration costs of renewables, and investment costs for nuclear in China are included based on reasonable assumptions regarding technology cost performance, which is a representation of technological flexibility and uncertainty in the future.

For scenarios from Pessimistic (P) to Optimistic (O), the technological performance is improved, allowing for more flexibility in the economic sector to react to the emissions penalty. The POL-T scenario was developed to test if coal-based generation technologies plus CCS can significantly reduce costs in the short-term (before 2030). Nuclear is the exception, as the cost set in POL-P and POL-T increases due to the larger possibility of the standard upgrade for nuclear power plants in China. The uncertainty of renewables (mainly wind and Solar PV) is primarily related to the associated integration cost and learning rate, here we emphasize the former, given the learning rate has been widely discussed in the literatures (for review, see [32]). There is a debate about how renewables should be developed in China (i.e., decentralized vs. centralized models; [33]), which will determine the scale of the integration cost. [Appendix B](#) describes the different technology assumptions of the three mitigation options in each case (see [Table 2](#)).

The policy dimension assumes either no carbon tax or a globally uniform, exponentially increasing (5% annually) carbon tax with a starting level of 30\$/tCO₂ (2005 price) in 2020. This relatively aggressive climate mitigation policy is consistent with the long-term target of limiting global warming to 2 °C [9] from previous modeling experience.

The following section presents the model results using four BASE scenarios and four policy scenarios. Moreover, BASE-PGas and POL-PGas are developed and used to test the sensitivity of gas prices, and POL-PBudget is added with an identical emissions pathway to POL-O (more stringent cap on emission). Each of these scenarios is based on the POL-P scenario. [Section 4.1](#) depicts the emissions and primary energy patterns and [Section 4.2](#) emphasizes the role of various technologies, their scales, and timings. [Section 4.3](#) discusses the economic impact due to technology variation and the introduction of a carbon tax.

³ Another methodological advantage of the assumption of a globally uniform carbon tax is that this avoids inter-regional redistribution of mitigation efforts (measured in equal marginal abatement cost) if technology assumptions in China are changed, compared to the global budget on emissions.

4. Results

4.1. The dynamics of emissions

4.1.1. Baseline scenarios

The scenarios show that due to continued economic growth, relatively plentiful coal endowments, rather low investment costs for conventional coal-fired power plants, and persistent inertia in the energy system, China will steadily increase its emissions (in absolute numbers and share of global emissions) over the next several decades without a carbon tax. From 2025 to 2035, China's share of global energy-related CO₂ emissions will peak at 32%, compared to 20% in 2005, and will decline thereafter ([Fig. 2](#)). The corresponding CO₂ emissions in China will increase from 7.3 Gt CO₂ in 2010 to a peak level of 18 Gt CO₂ in 2050, and will decline thereafter due to the economic efficiency improvement and decarbonization of the energy system, and the decline of the population. China's largest share in global emissions occurs 15–25 years earlier than its absolute emissions peak because other developing countries/regions, such as India and Africa, continue to increase their emissions over a longer time horizon while their economies catch up.

The increasing/decreasing availability of non-fossil energy technologies in BASE-P and BASE-O and cheaper coal-fired advanced mitigation technologies (in BASE-T) results in minor changes to emissions levels, which is relatively unaffected by the technology performance change at hand ([Fig. 3](#)). This is because the rapid increase of CO₂ emissions is mainly triggered by the large supply of competitive coal. With no emissions constraint, the option of using low- or zero-emissions technologies is not yet attractive in the baseline scenario cluster.

Using more coal, China is heavily reliant on imported coal from Russia and the USA⁴; therefore, the foreign dependency rate of coal will be greater and greater, as large as 70% by 2050. Although domestical coal can be recovered on a large scale, cheap coal is rather limited. Therefore, China's reliance on coal is dependent on relatively cheap coal imports, which will require large-scale transport infrastructure investments in the future, as well as a concern for security. Although the dependency rate seems surprisingly large from today's perspective, this finding is generally in line with other studies (e.g. [35]) that projects China's coal demand and supply potential.

In sum, coal is cheap; therefore, coal conversion technologies in China have a considerable competitive advantage over low-carbon technologies. Without a price on carbon tax, variations in technology assumptions will not affect the electricity generation mix to a considerable extent until 2050. Hence, technology policies are insufficient to achieve significant emissions reductions.

4.1.2. Policy scenarios

Compared to the baseline scenarios, the emissions patterns in the policy cases are largely restrained by the increasing carbon tax ([Fig. 3](#)). In POL-T and POL-O, energy CO₂ emissions in China will saturate quickly before 2020 at 9 Gt—approximately 50% of that in the BASE scenario—and will follow a declining trajectory towards negative emissions after 2070. This difference is due to the greater flexibility of technology options in these scenarios. In the POL-P scenario, the economic system loses some flexibility in the context of a carbon tax due to the rigidity of the technological assumptions. Therefore, the emissions peak is higher (0.2 Gt) in comparison to the other policy scenarios. In this pessimistic scenario, emissions will peak only by 2030 and decline thereafter.

⁴ The result is based on the way we frame the availability of coal in China. In REMIND, some other regions have larger reserves of coal that are easy to extract, especially the USA and Russia. See Bauer et al. (2013) [34] for more details.

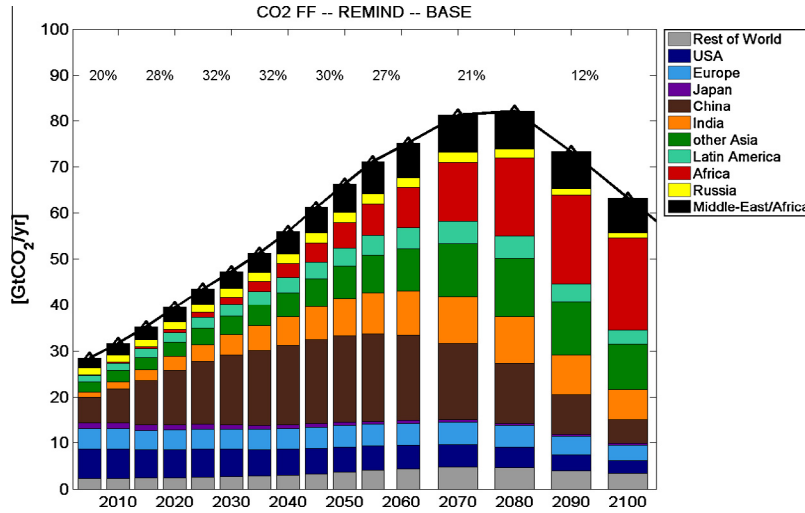


Fig. 2. China's energy CO₂ emissions share in the world between 2010 and 2100 in the BASE scenario.

While this difference exists across all the policy scenarios, China's largest share of global emissions occurs between 2020 and 2025 (27–28% of global emissions), which is slightly above current levels. The carbon tax policy is effective for reducing emissions globally, and most of China's mitigation achievements will be the result of reduced coal use.

In the policy scenarios, the energy system in the near- to mid-term is characterized by the substitution of natural gas for coal. This inter-fuel substitution is particularly important in the POL-P case, where other low-carbon technologies are not as important. Here, gas partially takes the role of nuclear and renewables, especially in the short- to medium-term. Thus, over the coming years, China needs to double its gas supply every 5–7 years. In 2030, gas consumption will reach 30 EJ/yr compared to 5 EJ/yr in 2010. This will lead to a rapidly increasing dependency on imported gas, with a share of over 70% by 2040. However, the effects of this phenomenon will depend on the price of imported gas and China's ability to expand its infrastructure. The price factor is examined in detail in Section 4.2.2 using a sensitivity analysis of the POL-P scenario.

4.2. Role of generation technologies

4.2.1. Baseline scenarios

A robust finding across the baseline scenarios is that coal-based generation is dominant throughout the time horizon (Fig. 4) until 2050 when coal becomes scarcer globally and world market prices increase. As a result, shares quickly decline as competition from non-fossil fuel technologies improves, particularly wind and solar. In the BASE-O scenario, which has the largest availability of renewables, the share of coal-fired generation in China's total power mix is still as high as 72% in 2050, which almost matches the current level. Coal-power generation is, without a carbon tax, the most competitive alternative in the range of uncertainties that we tested. The share of natural gas is lower due to the high cost compared to coal.

The roles of various non-fossil generation technologies are not sensitive to technology assumptions before the middle of the 21st century in all of the baseline scenarios (see Fig. 5, also showing the carbon emission of each scenario, accordingly).

The ranking of cumulative electricity generation (from highest to lowest) from 2010 to 2050 in the baseline scenarios is as follows: coal, hydro, nuclear, wind, and solar (mainly solar PV) in China (Table 3). This is the case regardless of whether the cost of

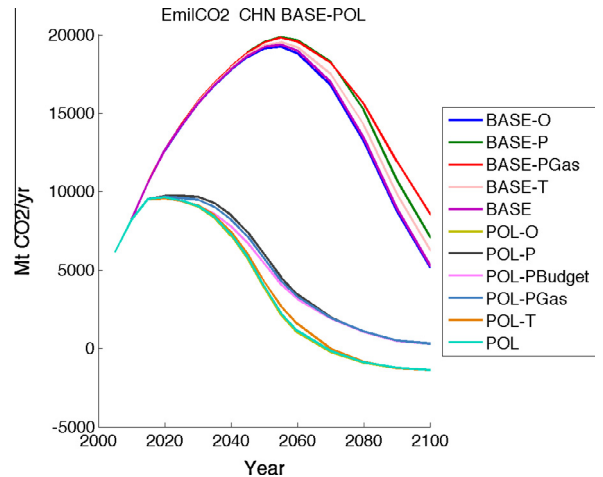


Fig. 3. Energy CO₂ emissions pathways in China for all scenarios.

nuclear increases and the barriers for renewable integration are high or low. Hydro and nuclear power currently have larger existing capacities than wind and solar technologies. Therefore, even if the latter two technologies grow at faster rates than the former two, it will take decades before the share of renewables will exceed that of hydro and nuclear, which the baseline scenarios do not consider.

4.2.2. Policy scenarios

The power mix in the policy cases results in a large deviation from the BASE pathway. The electricity sector is fully decarbonized before the end of the 21st century. The deployment of the three key advanced technologies in the tax scenarios is now much larger and covers a wider range (Fig. 6).

The scenarios with a rising carbon tax demonstrate a lower activity level of electricity generation (approximately 15–21% reduction measured in accumulated generation from 2010 to 2050), compared with the baseline scenarios. The reduction is strongest in the POL-P case with a 21% contraction rate.

The structure of electricity generation also changes significantly. In all the carbon tax scenarios, the stock of coal-fired power begins to phase-out immediately after 2010 and phase-out completely before 2060. The use of coal with CCS is limited in the

Table 3
Sensitivity of cumulated electricity generation to key technology assumptions.

(Unit: EJ)	1950–2010 (cumulative)	2010–2050 (cumulative)				
		Baselines		With climate constrains (excluding POL-T)		Optimistic technology (POL-T)
		Min	Max	Min	Max	
Coal	131*	1444	1471	442	489	502
Oil		7	7	7	7	7
Gas		128	129	251	447	356
Hydro	27	149	149	199	201	200
Nuclear	2.3	62	72	170	322	152
Wind	0.4	19	33	106	143	145
Solar PV	0.01	1	7	126	172	173
Biomass	0.01	4	4	10	12	10

* Due to data unavailability, the number is the electricity generated from all fossil fuels, including gas and oil.

POL and POL-O scenarios. The technology is phased-in quickly, and then it remains a niche market for a long time even in POL-T favoring the cheap CCS, because the carbon tax penalizes residual emissions; in fact, the penalty is high enough to drive up the cost of coal with CCS above the supply costs of nuclear and renewables. Therefore, the window of opportunity for CCS is limited, even with a carbon tax.

Another robust finding is that the carbon tax presents the largest risk for the coal industry. Measured in cumulated generation, the coal-power sector will shrink by 70%, measured in cumulated electricity generation compared to the baseline scenarios. Coal-fired generation will further shrink if the industry fails to adopt a technologically and economically viable route to CCS (e.g., the POL-P scenario); albeit, not by much (only a 3% accumulated electricity production difference across the POL cases). The gains for the fossil fuel sector are limited compared to no CCS, especially for “myopic” industry decision-making. Climate policy is crucial for the fossil industry, however CCS availability can reduce the negative impact only to some limited degree. These findings reveal a strong policy implication for the role of CCS, which will be discussed in Section 4.3.

Nuclear’s contribution to electricity generation and mitigation is highly dependent on its cost. Under the POL-P scenario, nuclear costs increase by 2% annually. Thus, the cumulated electricity derived from nuclear from 2010 to 2050 is only twice that of the BASE level; however, it can reach about four times that level in cases with no-increasing nuclear costs.

Although wind and solar PV do not play a significant role in the baseline scenarios, they become more promising in the policy cases. In fact, the ranking completely changes due to the fast reduction of investment costs that result from learning by doing (Fig. 7 shows the dynamics of endogenous investment cost changes). Renewable technologies rank above hydro in all the POL cases and above nuclear in expensive nuclear cases (i.e., POL-P and POL-T). The 100% increase of wind and solar PV in the near-term will lower the investment cost closer to the floor-cost within two to three decades (Fig. 7). This will make wind and solar PV technologies competitive with conventional power sources in the policy cases. Therefore, after 2030, the installation of wind and cheap solar PV, which has a lower floor-cost than wind, will make up more than 25% of the electricity mix by 2050 and 50% after 2070. The cumulated electricity generation from wind and solar in the policy cases is on par with conventional fossil-fuel, and makes up approximately ten-times that of the baseline scenarios (Table 3). In all scenarios, the differences in the energy mix are small after 2050 since all the policy scenarios result in solar PV and wind playing dominant roles in the energy mix. Renewables contribute substantially to emissions mitigation and are the long-term option (significant deployment after 2030, especially for solar PV) for deep emissions mitigation.

As mentioned in Section 4.1.2, the POL-P scenario is characterized by a significant increase in gas-use. This fast and significant increase substitutes coal in the electricity sector and removes the need for better coal-import infrastructure in China. If the availability of gas imports is reduced (by increasing the transport cost by 50%), its utilization in the power sector is also reduced (i.e., the POL-PGas scenarios). This is achieved by reducing the demand for electricity by using other input factors in the CES structure and substituting it with nuclear and solar PV (Fig. 6).

To summarize, the impact of the decline of technology flexibility on the effectiveness of the carbon tax (i.e., emissions reductions) is outstanding in the POL-P scenarios. Power sector emissions are only reduced by about 90% of other policy cases.

With this in mind, we created another scenario to test the sensitivity, POL-Pbudget, where we constrained the emissions of the power sector to the level of the POL-O scenario. This scenario is designed to reveal, if technology performance is worse and how the scale and timing of technology deployment changes, if we stick to the emission level as low as POL-O. The results show that the total electricity generation will contract to 78% of the BASE level, along with the deeper expansion of nuclear and renewables, which will replace natural gas, compared to the POL-P and POL-PGas scenarios.

4.3. Economic impact of technology variation and carbon policy

Economic impacts are of particular concern, because they indicate which technologies should be supported by governments and what the consequence of a climate policy commitment is. In the carbon policy scenarios, economic impacts are measured as GDP losses from BASE (no constraints on carbon emission) moving to POL mitigation cases, which are discounted (5%) and aggregated from 2010 to 2050 as a fraction of GDP in the baseline scenario.

The results show that GDP is barely affected in the baseline scenarios (Fig. 8). The main source of GDP loss is the carbon tax, which results in approximately 2–2.4% of GDP loss by 2050 in China and 1–1.5% globally.

Due to variations in the cost of technologies, mitigation cost differences range from 10% to 20% in policy scenarios. Where technology costs are high (e.g., the POL-P scenarios) cumulated GDP loss is as high as 2.4%⁵ in China and 1.5% globally. With the lower cost of mitigation technologies in the POL-O and POL-T scenarios, GDP loss can be as low as 2.1% for China and less than 1% globally.

The interdependency of China with the rest of world is also explored (Fig. 9). Under the carbon tax regime, because China faces inflexible mitigation conditions in POL-P, the burden on the other world regions is heavier compared to POL scenario, and the GDP

⁵ This means that China has the largest mitigation potential and a large share of mitigation in the policy cases occurs in China. The region that achieves mitigation is not necessarily the region paying the cost of mitigation.

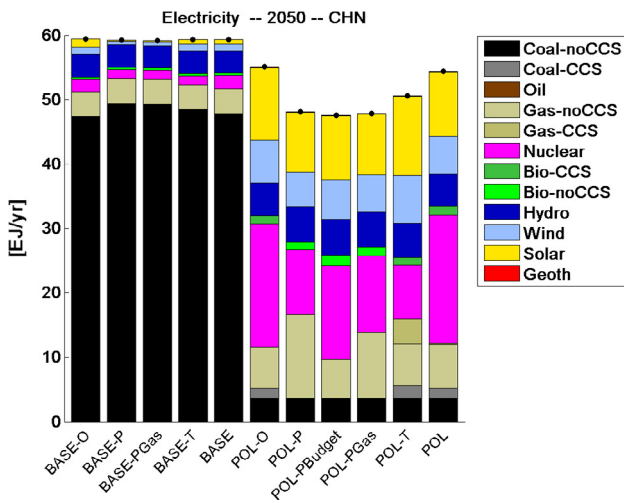
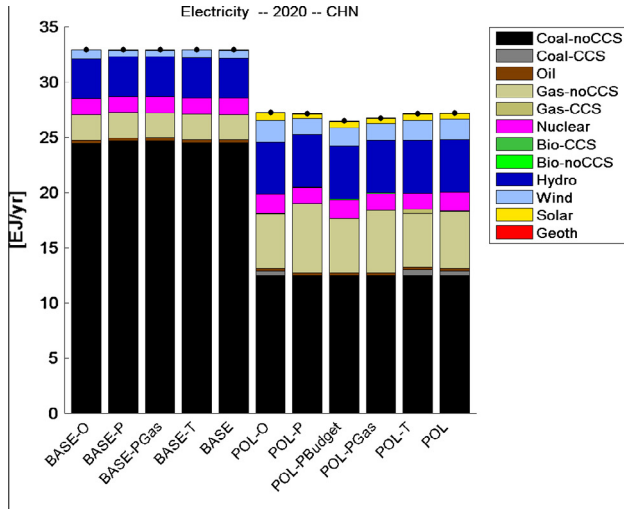


Fig. 4. Electricity generation mix for all scenarios.

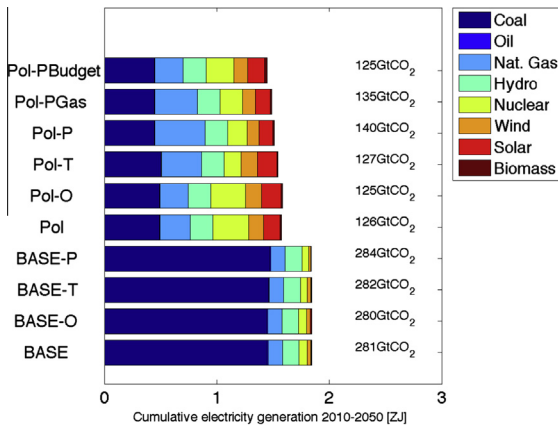


Fig. 5. Cumulative electricity generation in China by source and corresponding cumulative CO₂ emissions from 2010 to 2050.

loss is over 500 billion US\$ from 2010 to 2050 for the rest of world. In contrast, the POL-O scenario shows that if China continues to develop technological alternatives to coal and expands renewables in the power sector, the entire world will benefit in two ways: (1) global emissions and mitigation attributed to other regions will be

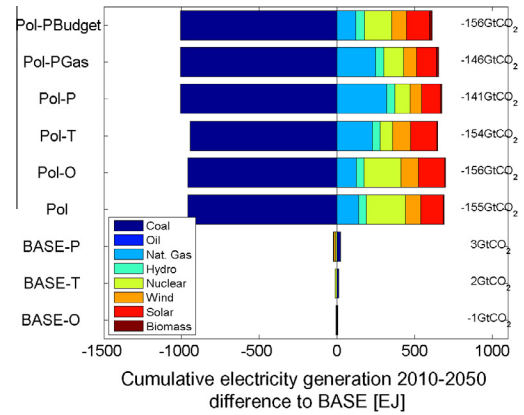


Fig. 6. Cumulative electricity generation compared to BASE from 2010 to 2050.

reduced and (2) China and other regions will experience higher GDP, due to the lower mitigation cost and/or mitigation need. The availability of advanced technologies to China not only benefits itself, but also at the same time, adding value to the mitigation efforts of others.

Economic losses are significantly larger in POL-P than in POL, POL-O, or POL-T. This shows that variations in nuclear and renewable performance only imply small changes in the optimal emissions time paths and cumulative discounted losses. The availability of CCS is the dominant factor affecting social economic loss, and accounts for most of the 0.3% difference in GDP between POL-P and POL. This is mainly because renewables and nuclear are phased-in much later, and is less important in the discounted value. In contrast, if CCS is available and cheap, it can supply low-carbon electricity in the near-term, which allows a smaller deviation from cheap fossil fuel use from the BASE pathway, and therefore results in a smaller cost.

If CCS is not available, the whole society will experience higher costs with higher saturation levels (0.2 Gt higher than with CCS). Moreover, in Section 4.2.2, we can see that CCS unavailability only reduces gross fossil-fuel use by 3% further in the policy scenario because it is the best short-term option and there are no appropriate alternatives to CCS; therefore, the energy system becomes more inflexible responding to carbon pricing in its absence. From this perspective, CCS is important for lowering compliance costs.

5. Discussion and conclusions

Without a carbon tax, China's emissions will increase steadily over the next several decades. Lowering the costs of nuclear and renewable energy will not change this result. This conclusion is robust for the first half of the century. The main reason is that fossil fuels and the related conversion technologies – particularly coal and coal-fired technology in China – remain much cheaper than the low-carbon alternatives. The phase-in of advanced wind and solar PV has already begun because of strong policy incentives from the government. However, the modeling shows that without a carbon tax, the pace and potential of these alternatives will be limited in an economically-rational world.

On the contract, if a globally uniform carbon tax that increases exponentially from the level of 30US\$/tCO₂ in 2020 is imposed, China's mitigation potential is larger than that of any of other region and the peaking of emissions will be earlier (in 2020 rather than 2050 or later). Furthermore, China's peak emission level will be 50% lower than in the BASE scenario without a carbon policy.

The effectiveness of technology policies for reducing emissions in the near-term and triggering improvements of low-carbon

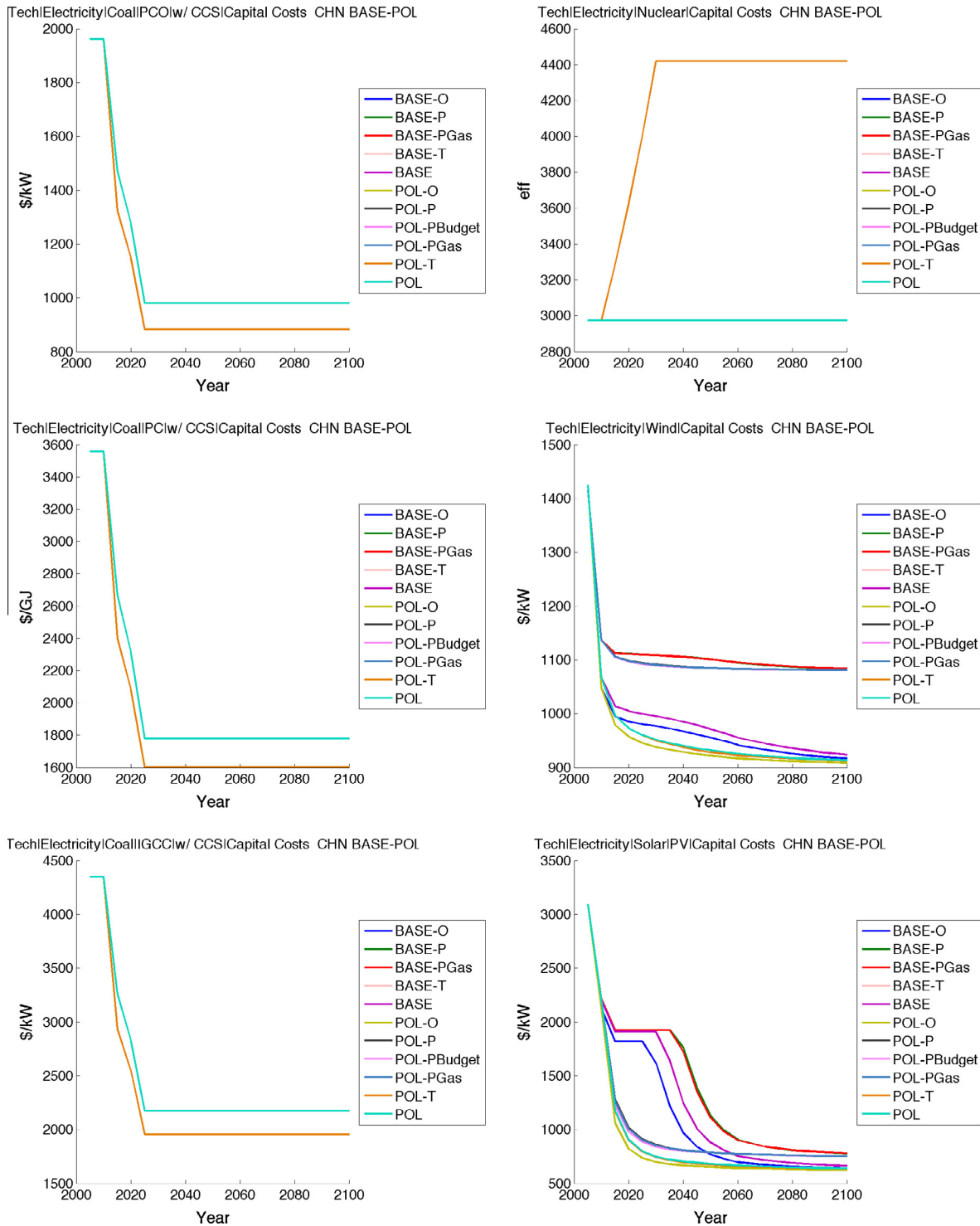


Fig. 7. Capital cost dynamics of all the scenarios.

technologies (via learning-by-doing) is crucial to reducing the cost of complying with the climate target. A carbon tax will result in a 2.4% GDP loss for China in scenarios where nuclear and renewable integration are expensive and where CCS is not available (i.e., POL-P). This figure could be as low as 2.1% if technology policies can effectively reduce the costs of key technologies, especially if CCS can be available.

The role of nuclear will largely be determined by the cost of investment. China has already regulated the construction of nuclear reactors: only third-generation technology standards are accepted, and the AP1000 technology cluster is dominant [36]. We expect that the cost of nuclear energy will escalate in China as safety standards for nuclear power-plants increase, which will significantly affect diffusion patterns in the power sector (Bauer

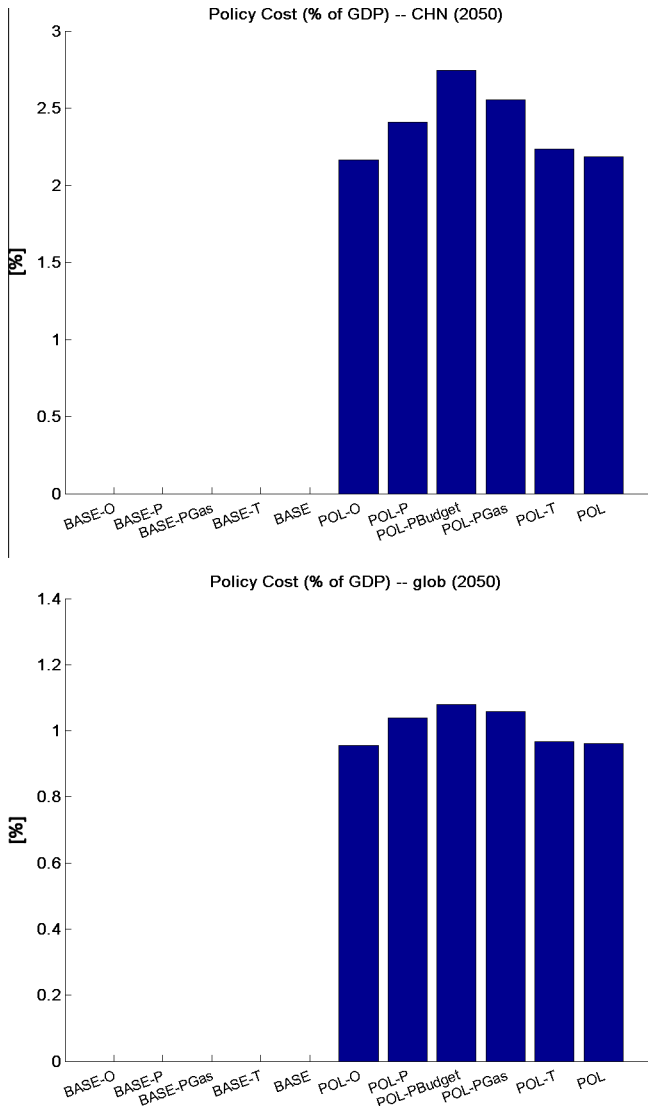


Fig. 8. Discounted GDP loss in the baseline and policy scenarios.

et al., 2012a). Nevertheless, domestic manufacturing can cut the cost of nuclear by over 70% [37], which is the crucial factor to make nuclear a competitive alternative to coal-fired generation.

Wind and solar PV are cutting-edge technologies that are entering the commercialization stage. Under a climate policy, they are expected to become competitive within one decade through the effects of learning-by-doing, if they continue to receive widespread support for their expansion. Renewables will be the long-term choice for decarbonizing the electricity sector, given their increasing competitiveness over time and the fact that they produce zero emissions. However, they will only contribute at a notable scale to China's mitigation strategy after 2030 because now they have a relatively low presence in the market.

CCS is important for reducing the economic impact of climate change mitigation, but its window of opportunity is limited to the near future, because other options, such as renewables, will become more competitive over time. CCS is important for lowering compliance costs, but is not effective enough for the fossil fuel industry to maintain its market share. Strong support for CCS is necessary if its mitigation effects are desired.

In summary, there is no single technological solution option to climate mitigation. However, without climate policies, China will

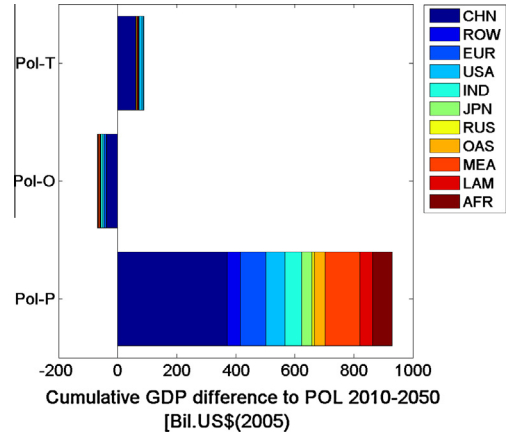


Fig. 9. Cumulative GDP difference, compared to POL between 2010 and 2050, Bil.US\$ (2005).

continue to use coal on a large scale. Climate change mitigation in the Chinese power sector is mainly concerned with reducing CO₂ emissions from coal. This study suggests the importance of a CCS-support program to contribute to short-term mitigation in the absence of other acceptable options. The cost dynamics of nuclear power plant construction will determine the future of China's power sector. Renewables are the most important long-term solution for deep emissions mitigation although, significant deployment will only occur after 2030, especially for solar PV. Creative policies such as alternative investment, technology innovation, and climate protection strategies should be explored to provide the best available information to policy-makers about appropriate long-term solutions.

This study reveals three areas for further research. First, in this paper, individual regions learn and reduce investment costs in a fragmented way without inter-regional spillover, even in the long-term. This removes the complexity of inter-regional interaction for the advanced technologies. The effect of research and development, technology transfers, and global convergence/divergence on investment costs is beyond the scope of this country-level study; however, it is a worthwhile topic for future research on global issues and technology transfer policies.

Second, we highlight that a uniform, increasing CO₂ tax covering all regions and sectors uniformly, which have important and critical impacts on the evolution of energy system, is really a strong assumption. Disconnect of this assumption necessary to achieve the 2° target and the realistic climate protection regime is obvious. Given our emphasis focused on the technology dimension, the role of this uniform tax is indeed a simplified treatment, in order to provide a benchmark for the analysis and policy implication. So far, delayed mitigation action, fragmented climate policy and incomplete climate policy participation are more realistic. If these deviations from idealized policy assumptions are considered, the results of the paper might be changed, e.g. in term of the pace for entering the market of the low carbon options. This work has partly been done (e.g. [9]) and will be conducted further with the new development of the model and policy agenda.

Third, our assumptions regarding the techno-economic performance of energy technologies could be viewed as controversial. Some of our conclusions are robust (e.g., the importance of CCS and the long-term importance of renewables), while others are dependent on our key assumptions regarding the dynamics of investment costs (e.g., the role of nuclear and grid-associated renewables). Associated cost along with new grid construction reflecting the integration necessity of renewable expansion, the

Appendix A. Regional adjustment factor for the lowest investment cost and adjustment principle

Region	Country group/ typical country	Remarks on adjustments	Adjustment factor for coal-fired generation					Adjustment factor for wind	Adjustment factor for SPV	Adjustment factor for nuclear
			IGCC	IGCCC	PC	PCC	PCO			
EUR		Good data source	1.1	1.1	3.0	1.7	3.0	1.6	1.3	1.5
RUS	Russian	Relatively good data source. Nuclear in RUS is generally cheaper because the technology is already owned, and other options are slightly more expensive than in the US and EUR.	1.1	1.1	3.3	1.8	3.3	1.6	1.3	1.1
USA	United States	Good data source. Investment level is generally higher due to strict regulations, expensive labor, and other factors.	1.6	1.5	3.2	1.8	3.2	1.6	1.3	1.2
JPN	Japan	Pattern is similar to USA.	1.1	1.1	4.1	2.1	4.1	2.2	1.3	1.1
CHN	China	Significantly cheaper for thermal power because it is produced domestically; cheaper than renewables and nuclear.	1.0	1.0	1.0	1.0	1.0	1.2	1.0	1.0
IND	India	Poor data availability in most cases, so uses the cost level of EUR due to less technological capacity.	1.1	1.1	3.0	1.7	3.0	1.0	1.0	1.5
AFR	South Africa	High cost for thermal and nuclear due to less practice, moderate for hydro and other options.	1.1	1.1	3.0	1.7	3.0	1.6	1.2	1.5
LAM	Brazil	Partly from IEA (2011) and others similar to IND.	1.1	1.1	2.0	1.3	2.0	1.6	1.3	1.5
MEA	Middle East	Pattern is similar to AFR.	1.1	1.1	3.0	1.7	3.0	1.6	1.3	1.5
OAS	Southeast Asian	Pattern is similar to IND.	1.1	1.1	3.0	1.7	3.0	1.6	1.3	1.5
ROW	Rest of world (mainly, Korea and Canada)	No change.	1.1	1.1	3.0	1.7	3.0	1.6	1.3	1.5

Note: The investment value was based on the market exchange rate. Author's estimation based on [4,5].

Appendix B. Parameters for the investment costs of electric generation technologies

	Pessimistic development (P)	Reference	Optimistic development (O)	Optimistic clean coal technology scenarios (T)
Coal + CCS	CCS unavailable	CCS unavailable	CCS available	Cheaper combination of CCS with coal-fired generation available (investment cost declines by 10% compared to the BASE scenario); IGCC is cheaper, with a 2% annual decline in investment costs.
Renewable	Grid construction demand for integration is 20% more than BASE; floor-cost for learning	Grid capacity expansion needed for 2/3 electricity transmission from	More decentralized electricity model; integration grid demand is improved by	Same as reference case.

Appendix B (continued)

	Pessimistic development (P)	Reference	Optimistic development (O)	Optimistic clean coal technology scenarios (T)
	technologies is limited to 120% of the BASE level.	increased wind and solar PV power generation.	80% in the BASE scenario; learning rate is 10% larger than in the reference case.	
Nuclear	Investment cost increases by 2% annually from 2010 to 2030.	Investment cost is 2500\$/kW	Same as reference case.	Investment cost increases by 2% annually from 2010 to 2030.

dynamics of nuclear investment costs should be reviewed more carefully through specific case studies.

Acknowledgments

Funding from the Alexander von Humboldt-Foundation's International Climate Protection Fellowship is gratefully acknowledged by Shuwei Zhang. Funding from the German Federal Ministry of Education and Research (BMBF) in the Call "Economics of Climate Change" (funding code 01LA11020B, Green Paradox) is gratefully acknowledged by Nico Bauer.

References

- [1] Intergovernmental Panel on Climate Change (IPCC). In: Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE, editors. *Climate change 2007: impacts, adaptation and vulnerability: contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*, Cambridge: Cambridge University Press; 2007.
- [2] Wang K, Wang C, Chen J. Analysis of the economic impact of different Chinese climate policy options based on a CGE model incorporating endogenous technological change. *Energy Policy* 2009;37:2930–40.
- [3] National Development and Reform Commission (NDRC). *China's National Climate Change Programme*, Beijing, 2007. <http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File188.pdf>, accessed at 10.10.11.
- [4] International Energy Agency (IEA). *Projected costs of generating electricity – 2010 update*. Paris: OECD, IEA, NEA, 2011.
- [5] International Renewable Energy Agency (IRENA). *Renewable energy technologies: cost analysis series*. 2012, <www.irena.org>, access at 01.05.12.
- [6] Wetterlund E, Söderström M. Biomass gasification in district heating systems – the effect of economic energy policies. *Appl Energy* 2010;87(9):2914–22.
- [7] Karlsson M. The MIND method: a decision support for optimization of industrial energy systems – principles and case studies. *Appl Energy* 2011;88(3):577–89.
- [8] Bauer N, Brecha RJ, Luderer G. Economics of nuclear power and climate change mitigation policies. *PNAS* 2012;109:16805–10.
- [9] Luderer G, Pietzcker RC, Kriegler E, Haller M, Bauer N. Asia's role in mitigating climate change: a technology and sector specific analysis with ReMIND-R. *Energy Econom* 2012;34:5378–90.
- [10] Zhou Wenji, Zhu Bing, Fuss Sabine, Szolgayová Jana, Obersteiner Michael, Fei Weiyang. Uncertainty modeling of CCS investment strategy in China's power sector. *Appl Energy* 2010;87(7):2392–400.
- [11] Liu Wen, Lund Henrik, Mathiesen Brian Vad, Zhang Xiliang. Potential of renewable energy systems in China. *Appl Energy* 2011;88(2):518–25.
- [12] Mathiesen Brian Vad, Lund Henrik, Karlsson Kenneth. 100% Renewable energy systems, climate mitigation and economic growth. *Appl Energy* 2011;88(2):488–501.
- [13] Yang Chi-Jen. A comparison of the nuclear options for greenhouse gas mitigation in China and in the United States. *Energy Policy* 2011;39(6):3025–8.
- [14] Calvin Katherine, Clarke Leon, Krey Volker, Blanford Geoffrey, Jiang Kejun, Kainuma Mikiko, et al. The role of Asia in mitigating climate change: results from the Asia modeling exercise. *Energy Econom* 2012;34(3):S251–60.
- [15] Viebahn Peter, Daniel Vallentin, Samuel Höller. Integrated assessment of carbon capture and storage (CCS) in the German power sector and comparison with the deployment of renewable energies. *Appl Energy* 2012;97:238–48.
- [16] Liang Qiao-Mei, Wei Yi-Ming. Distributional impacts of taxing carbon in China: results from the CEEPA model. *Appl Energy* 2012;92:545–51.
- [17] Duan Hong-Bo, Fan Ying, Zhu Lei. What's the most cost-effective policy of CO₂ targeted reduction: an application of aggregated economic technological model with CCS? *Appl Energy* 2013;112:866–75.
- [18] European Commission. *Energy roadmap 2050: impact assessment and scenario analysis*. Working paper, 2011, http://ec.europa.eu/energy/energy2020/.../roadmap2050_ia_20120430_en.pdf.
- [19] Larson Eric D, Zongxin Wu, DeLaquil Pat, Wenyong Chen, Pengfei Gao. Future implications of China's energy-technology choices. *Energy Policy* 2003;31(12):1189–204.
- [20] OECD/IEA. *Energy technology perspectives 2012 – pathways to a clean energy system*, ISBN 978-92-64-17488-7, 2012.
- [21] Xunmin Ou, Xiaoyu Yan, Zhang Xiliang. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. *Appl Energy* 2011;88(1):289–97.
- [22] Zhu Lei, Fan Ying. A real options-based CCS investment evaluation model: case study of China's power generation sector. *Appl Energy* 2011;88(12):4320–33.
- [23] Hoffmann Bettina Susanne, Szklo Alexandre. Integrated gasification combined cycle and carbon capture: a risky option to mitigate CO₂ emissions of coal-fired power plants. *Appl Energy* 2011;88(11):3917–29.
- [24] Liang Xi, Reiner David, Li Jia. Perceptions of opinion leaders towards CCS demonstration projects in China. *Appl Energy* 2010;88(5):1873–85.
- [25] Middleton Richard S, Eccles Jordan K. The complex future of CO₂ capture and storage: variable electricity generation and fossil fuel power. *Appl Energy* 2013;108:66–73.
- [26] Jiang Xi, Akber Hassan Wasim A, Gluyas Jon. Modelling and monitoring of geological carbon storage: A perspective on cross-validation. *Appl Energy* 2013;112:784–92.
- [27] Liu Wen, Lund Henrik, Mathiesen Brian Vad, Zhang Xiliang. Potential of renewable energy systems in China. *Appl Energy* 2011;88(2):518–25.
- [28] Leimbach M, Bauer N, Baumstark L, Edenhofer O. Mitigation costs in a globalized world: climate policy analysis with ReMIND. *Environ Model Assess* 2010;15:155–73.
- [29] Bauer N, Baumstark L, Leimbach M. The ReMIND model: the role of renewables in the low-carbon transformation – first best vs. second-best worlds. *Climatic Change* 2012;114(1):145–68.
- [30] Baure N. Carbon capturing and sequestration: an Option to buy time? Doctor dissertation, 2005, <http://www.pik-potsdam.de/members/edenh/theses/phdbauer.pdf>.
- [31] Jiao S.J. Searching for the developing paths of IGCC power plant in China. *Gas Turbine Power Generation Technology* 2007, 9 (1): 6–14 (in Chinese), cited from Liu H, Ni W, Li Z, Ma L. Strategic thinking on IGCC development in China. *Energy Policy* 2008;36:1–11.
- [32] Lindman Åsa, Söderholm Patrik. Wind power learning rates: a conceptual review and meta-analysis. *Energy Econom* 2012;34(3):754–61.
- [33] Fang, Xiaoju. New question on wind power: centralized or decentralized. *China Energy Newspaper*. http://paper.people.com.cn/zgnyb/html/2012-01/16/content_995409.htm, 2012.
- [34] Bauer N, Mouratiadou I, Baumstark L, Brecha R, Luderer G, Kriegler E. *Global Fossil Energy Markets and Climate Change Mitigation – an analysis with ReMIND*. Climatic Change, 2013, in press.
- [35] Li Boqiang, Liu Jiang-hua. Estimating coal production peak and trends of coal imports in China. *Energy Policy*, 2010, 38(1): 512–519.
- [36] State Council. *China's Energy Policy 2012*, White paper, <http://www.chinadaily.com.cn/china/2012-10/24/content_15843745.htm>
- [37] Tian J. China will be nuclear giant by 2020. Interviewed by Yicai. <http://www.yicai.com/news/2010/06/367467.html>, 2010.