Model-based Exploration of the Feasibility of China's Climate Change Ambitions: Investigating CO_2 Emission Reduction of the Electric Power Industry

Menglin Xia,* **Jici Fan**,† **Bramka Arga Jafino**,‡ and **Erik Pruyt**§

Delft University of Technology – Faculty of Technology, Policy and Management,Jaffalaan 5, 2626 BX, Delft, the Netherlands

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Abstract

China has pledged to take measures to reach a peak in its CO_2 emissions around 2030 and to curtail the 2030 emission intensity of GDP compared to the 2005 level by at least 60%. With over 70% electricity generated from coal, the electric power industry is a focal area of emission reductions. In this study, a system dynamics model was used to explore the feasibility of realizing these ambitions under the current economic development plan and to identify leverage points for effective policy intervention. Our simulation results show that cutting down the emission intensity is easier to realize than reducing annual CO_2 emissions. However, both targets are hard to meet, which means that without further policy intervention China may not be able to keep its commitments. Five policies are therefore tested here. Enforcing carbon capturing and storage systems in coal-fired power plants is found to be the most effective policy to stabilize CO_2 emissions, although it was insufficient to meet the overall goal. All five policies together are sufficient though, even under deep uncertainty, for average annual GDP growth rates up to 7% between 2015 and 2050.

Keywords: CO_2 emissions; Electric power industry; Emissions reduction; System dynamics; China

*mlxia1991@gmail.com, +31651653669
†Jici.fan.1@gmail.com, +31651653526
‡Bramkaarga@gmail.com
§E.Pruyt@tudelft.nl

1 Introduction

Over the past years, China's carbon dioxide (CO_2) emissions has witnessed an upsurge as a result of the rapid economic growth and the excessive consumption of carbon-intensive fossil fuels (Chen, Chen, & Chen, 2013). Earlier than expected, China overtook the United States and has become the world's largest CO_2 emitter since 2007 (Minx et al., 2011). In 2014, China's CO_2 emissions reached 10.54 billion tons, which accounted for 29.5% of the global CO_2 emissions (Olivier, 2015). The rapid growth of CO_2 emissions in China incurs high international pressure (Hao, Liao, & Wei, 2015). The country's reaction to restrain CO_2 emissions is widely concerned.

China is resolved to control its CO_2 emissions. In 2014, the USA and China released a joint announcement on climate change. China committed to continuously reduce its carbon intensity of GDP by 60% to 65% from the 2005 level by 2030. In addition, the annual CO_2 emission of the country is promised to peak by 2030. This is an ambitious plan perceived by the external world, though indicating China's willingness to take responsibility. Whereas, it is also a big challenge to the country.

During the 2015 United Nations Climate Change Conference in Paris, the reduction of CO_2 emissions in power industry was emphasized. In China, electricity production is the largest source of emissions, accounting for more than 40% of the total amount (Zhao, Ma, & Yang, 2013). The most important electricity generation approach in China is still coal-fired power, which constitutes more than 70% of the current electricity supply. Thus, reducing CO_2 emissions in electricity generation is an essential part in meeting the overall target.

However, curtailing CO_2 emissions in electric power industry is challenging. China is currently in the process of industrialization and urbanization (Jiang & Lin, 2012). The growing GDP inevitably requires large electricity supply, which leads to the boom of carbon emissions (Yuan et al., 2014). Chinese government has taken steps to mitigate CO_2 emissions in power industry, such as by encouraging the development of renewable energy (The White House, 2015). However, the projected renewable energy development may not be able to meet the fast rising electricity demand (IRENA, 2014). As a result, supplementing with additional coal fired power plants maybe still necessary. These facts reinforce the challenge of reducing CO_2 emissions while keeping the rapid growth of GDP.

China's CO_2 emission is an active research area where various tools and mathematical models have been applied. Lawrence Berkeley National Laboratory projected that China's emissions will approach a plateau in 2025 or 2030 under different scenarios (Zhou, 2011). Yuan et al. (2014) reviewed the research of CO_2 environmental Kuznets curve simulation models and proposed a new analytical framework. They maintained that China's CO_2 emissions would scale up along with the size of economy reaching its peak around 2030 to 2035. However, these researches are mostly conducted from a complete picture with all sectors included. The research that particularly focuses on CO_2 emissions in electric power industry is not widely available. Since electricity generation is the main source of CO_2 emissions, it is of great significance to investigate the trend and mitigating measures of CO_2 emissions from this perspective.

At the same time that these ambitious targets were set up, Chinese government implemented many new regulatory strategies to curb CO_2 emissions in electrical industry. However, these changes are not thoroughly discussed in previous papers. Studies on the influence of these new changes on the future CO_2 emissions are of great value. Here, a system dynamics model built in Vensim is applied to bridge the projections of CO_2 emissions and policy evaluation. By quantifying the effectiveness of policies, policy makers have better information for making decisions.

System dynamics models can be helpful in understanding environmental systems and exploring climate policies (Ford, 1999; Fiddaman, 2002; Fiddaman, 2007). Many system dynamics researches regarding carbon emissions in energy industry have been performed. Aslani, Helo, and Naaranoja (2014) built a model purely focusing on the development of renewable energy resources in Finland. Anand, Vrat, and Dahiya (2006) modeled the CO_2 emissions in Iranian cement industry under different scenarios. As for the CO_2 emission issue in China, many researches have been done on a region-level. System dynamics models were developed to model the energy consumption and CO_2 emissions in major cities such as Beijing and Shanghai (Feng et al., 2013; Yan and Zuo, 2015). In addition, Liu et al. (2015) evaluated the possible ways for China to realize its 2020's emission target. However, the policies they studied were quite limited in renewable energy development.

This study focuses on Chinese government's latest carbon emission reduction promise in 2014 US-China joint announcement and 2015 Paris climate change conference. The paper aims to study the feasibility for China to achieve the carbon emission reduction targets in 2030 in electrical power industry. Additionally, seeking for effective policies to restrain CO_2 emissions are also addressed.

The rest of the paper is organized as follow: first of all, a full overview of the model is given, in which modeler's thoughts and main modelling decisions are presented. Description of sub-models is followed to provide more detailed information. Then, validation and sensitivity tests are conducted. Base case simulation results exhibit the behaviors of the model without further policy intervention. Based on that, five policies are developed and their effectiveness is evaluated. Furthermore, the robustness of these policies are tested under deep uncertain context. Finally, these findings and reflections are summarized in the conclusion.

2 Model Description

2.1 Model boundaries

This study is focused on the emission target of Chinese electric power industry in 2030. In this case, a little longer time horizon from 2000 to 2050 is chosen.

A set of necessary and aggregated elements are selected to generate and present the behavior of interests (Sterman, 2000). Unnecessary elements are deliberately omitted. Two categories of elements can be defined in the model: elements that have interaction with other elements in the system are modeled as endogenous variables and those which are not sufficiently affected by the system are exogenous variables (Pruyt, 2013). The bull's-eye diagram in Figure 1 provides a general overview of all the elements in the model and fully explains the boundary of the model.

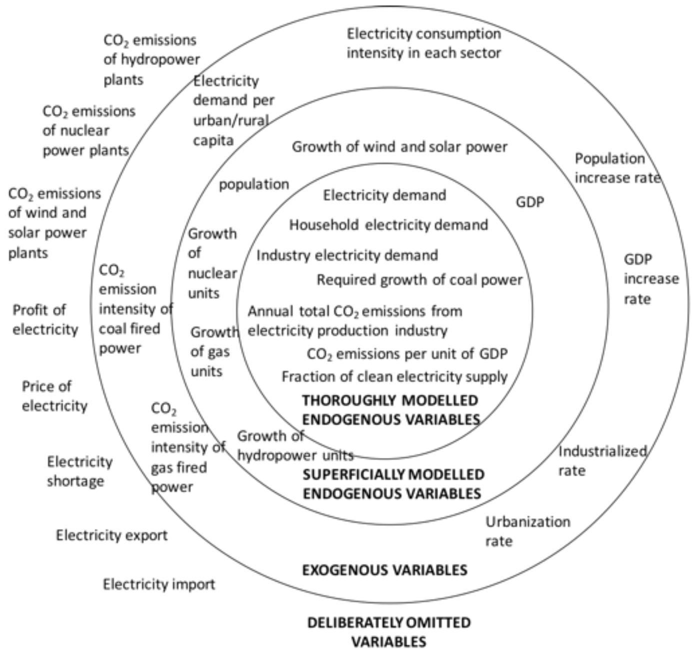

Figure 1: Bull's eyes diagram.

An important part excluded from this model is the price and market mechanism of different electricity sources. The costs and profits may do have influence on the investment and development. However, since the model aims to explore the CO_2 emissions of Chinese power industry from a holistic perspective, the deeper and specific causes of the development are beyond the boundary of the model and can be neglected.

Based on the data, the consumption and supply of electricity are equivalent in China. Import and export of electricity in China are inconsiderable, so they are deliberately omitted as well. Compared with coal-fired power plants and gas power plants, solar, wind, hydro and nuclear power plants emit much less CO_2. Hence, their emissions are neglected.

2.2 Conceptual Model

The rapid GDP growth is the main driving force of total electricity demand in China. Apart from the electricity from clean energy sources, most of the electricity demand is fulfilled by coal-fired power plants which emit considerable amount of CO_2. In the past decades, total CO_2 emissions in China have almost doubled. The continuing rise of coal electricity supply and annual CO_2 emissions cause both high domestic air pollution pressure and international pressure on emission reduction, which accelerate the development of clean energy and hinder the sustainable growth of GDP.

Key performance indicators (KPI) in this study are total annual CO_2 emissions and CO_2 intensity of GDP in electricity generation. In order to show the fundamental idea behind the model and the dynamic of these key parameters, a highly aggregated causal loop diagram (CLD) is provided in Figure 2. Four loops are identified in this aggregated CLD.

1. Growth of clean electricity supply driven by air pollution pressure: growing coal electricity supply reinforces the domestic pressure on air pollution. The air pollution awareness provides positive environment for development of clean energy sources.
2. Growth of clean electricity supply driven by international CO_2 emission reduction pressure: the inspection from other countries and international organizations on Chinese total CO_2 emissions pushes the development of clean energy capacities in China.
3. Demand of coal electricity drives supply: continuous rise of total electricity demand requires more coal electricity, which should be met by coal electricity supply.
4. Increase of CO_2 emissions due to the development of gas power plant: due to the domestic and external pressure, the development of clean energy capacities, including gas electricity capacity, is accelerated. Increasing gas electricity emits more CO_2, while it is much greener than coal electricity.

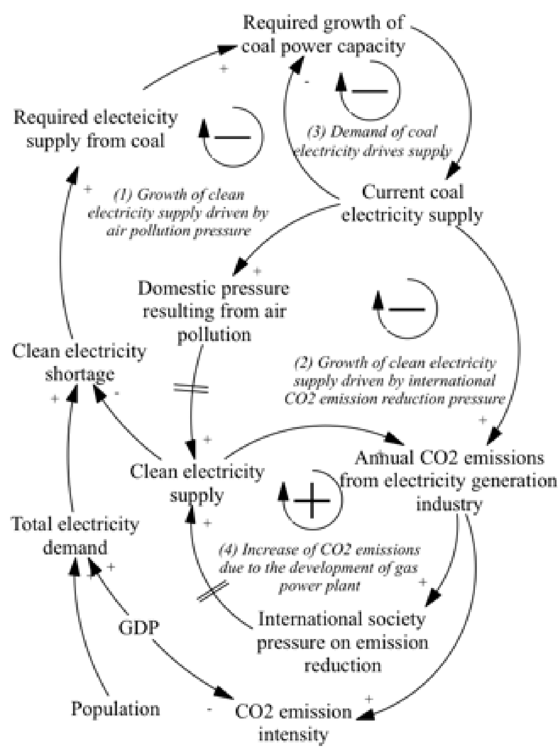

Figure 2: Causal Loop Diagram.

2.3 Sub-models

The model is mainly comprised of three sub-models: electricity demand, electricity supply and CO_2 emissions. Their interrelationship and interactions can be summarized as follow: Electricity demand determines the electricity supply. CO_2 emissions that originate from electricity production are dependent on the amount and fraction of different electricity sources. Considering the huge pressure of carbon emission reduction, the amount of CO_2 emissions influences the development of clean electricity sources. Electricity from gas power plant is considered as clean electricity in this paper, as coal-fired electricity is still dominant in China.

For the electricity supply sub-model, it can be further divided into two parts. The first part is the electricity supply from clean energy sources, including electricity generated from solar, wind, hydropower, nuclear and natural gas. The second part is the electricity supply met by coal-fired power plants. Under current and foreseeable future policy, clean electricity has the priority to be sold on grid (The White House, 2015). So ideally the amount of coal electricity is determined by the deficiency of clean electricity supply.

Currently, electricity production is already superfluous. The average annual utilization hour of power-generating equipment in coal-fired power plants is 1200 hours lower than the design value, which is 5500 hours per year (ASKCI, 2016). This oversupplying circumstance is believed to hold in the long term. Based on these facts, this paper assumes that there will be no scarcity of electricity supply in China.

1. Sub-model of electricity demand

Figure 3 shows that the total electricity demand is the sum of household electricity demand and industry electricity demand. The determinants of household electricity demand are population and urbanization rate. The demand will ascend with the growth of population. As the urban residents' electricity consumption (600 KWh per person per year) is significantly larger than the rural residents' (200 KWh per person per year) (China Electricity Council, 2015), urbanization level is also believed to notably affect the household electricity demand.

GDP growth is the main driving force for escalation of total industry electricity demand. Electricity is a basic good and sufficient electricity supply is the foundation of GDP development. The rise of GDP demands more electricity. The total industry electricity demand can be modelled as the sum of the demands from primary industry, secondary industry and tertiary industry. Factors that have big influences on the electricity demand of each industry are the fraction of its production value in GDP and the amount electricity consumption required for per unit of output (electricity consumption intensity). Since the electricity consumption intensity in primary industry and tertiary industry are approximate (China Electricity Council, 2015), the electricity demand from these two sources can be counted together. Currently, secondary industry takes up approximately half of GDP and its electricity consumption intensity (0.16 KWh/CNY) is much larger than the others (0.02 KWh/CNY). Thus, most of the electricity demand may come from secondary industry.

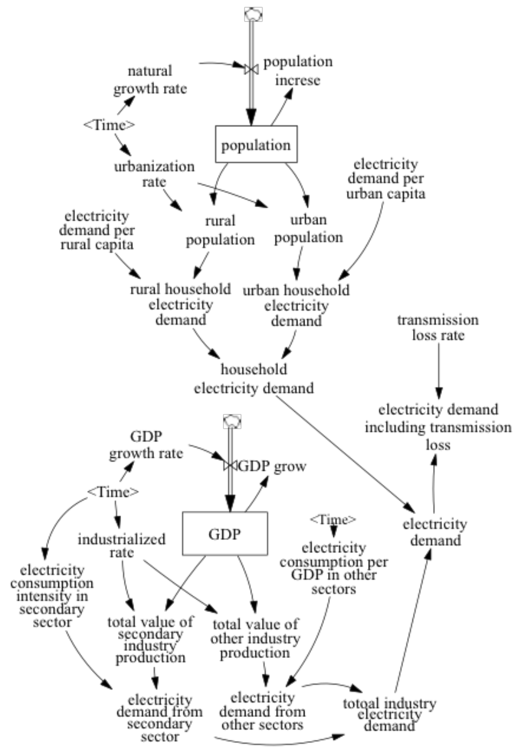

Figure 3: Sub-model of electricity demand.

2. Sub-model of electricity supply

The electricity supply sub-model consists of two parts: the electricity supply from clean electricity sources and the electricity supply from coal fired power plants.

(1) Clean electricity supply

Figure 4 provides an overview of the composition of clean electricity supply. The clean energy sources which contribute less than 1% of total electricity supply are omitted in the model. As wind and solar energy have similar lifetime and operating hours, they are modelled together. Finally, four categories of clean electricity sources are presented in the model: wind and solar energy, nuclear energy, hydropower and natural gas power (China Electricity Council, 2015). For each type of energy, the amount of electricity generation is the active capacity times the operating time. The capacity is simulated as a stock with the inflow of net capacity growth. The historical growth rates are derived from published data from China Electricity Council (2015). The capacity growth data for the future are the projections from official reports and plans (China Electricity Council, 2015). These data are deemed to be influenced by other external factors as well, such as the domestic pressure resulting from air pollution of coal-fired power plants and the international society pressure. External pressure will stimulate the development of renewable sources.

(2) Sub-model coal fired capacity increase

Total electricity generated from coal is modelled as the deficiency of clean electricity. Currently, a problem that the coal fired sector encounters is the excessive capacity. More ca-

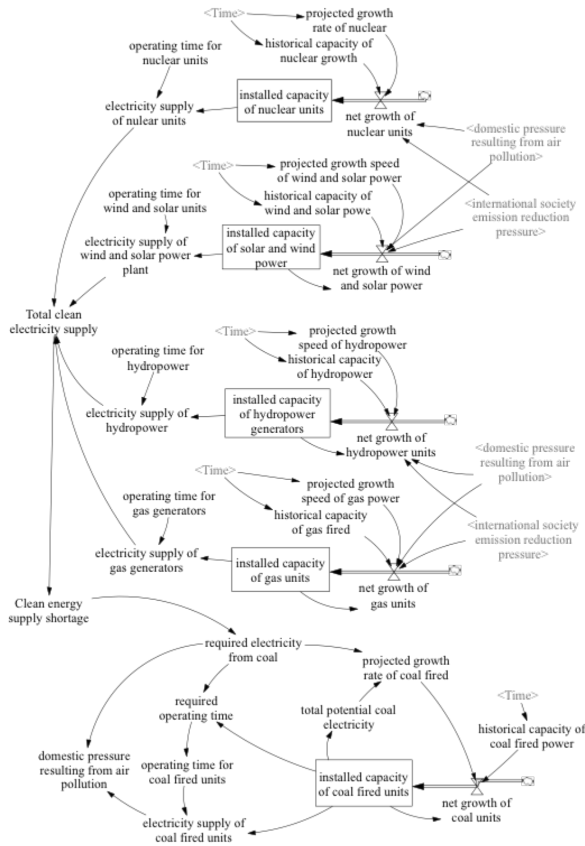

Figure 4: Sub-model of electricity supply.

pacity is under construction than what is actually required (China Electricity Council, 2015). In order to provide effective information to tackle this problem, a hypothesized situation is constructed here. This model assumes that the operating time of each coal-fired power plant can be ideal, which is the time as originally designed. For most coal-fired power plants, this value is 5500 hours per year (China Electricity Council, 2015). As Figure 4 shows, new capacity is planned only when the existing capacity can not meet the demand. The capacity derived in this model is the minimum required capacity to satisfy the total electricity demand. This data is helpful to provide policy makers with a beneficial reference on deciding annual projected capacity. Electricity supply from coal units is modelled as a product of installed capacity of coal units and actual operating time. Electricity production from coal is also a major source of air pollution in China. With growing concern about the environment, the rise of coal electricity production could result in more domestic pressure, which tends to against the growth of coal electricity and will urge the government to accelerate the development of clean energy sources.

3. Sub-system CO_2 emissions

CO_2 emissions in electricity production is mostly from coal fired power plants and a small proportion is from gas power plants. The amount of CO_2 emissions from each category equals to its CO_2 emission intensity times the corresponding amount of electricity production.

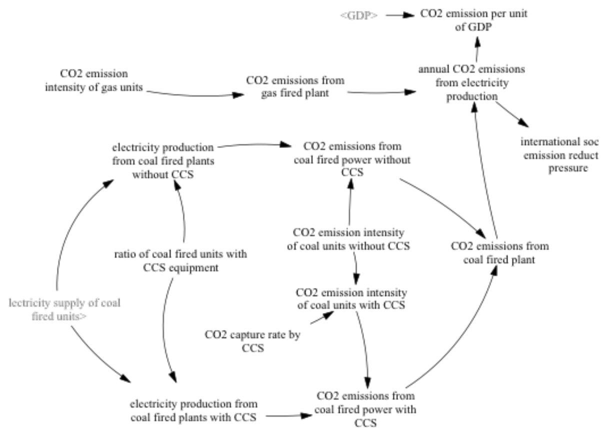

Figure 5: Sub-model of CO_2 emissions.

Carbon capture and storage (CCS) system is a system aims to reduce carbon emissions in coal-fired power plants. Currently, no power plant is equipped with CCS system in China, though this technique is expected to spread very fast in the future (Wang & Du, 2016). It is constructed as one of the policies proposed to tackle the emission problem.

International society pressure on carbon emissions is modelled as the annual growth rate of total CO_2 emissions. This pressure will probably urge China to spur the development of renewables and energy saving technologies.

3 Model validation

For the model validation, firstly, outcomes of this model are compared with projections from other studies. After that, structural validation was applied as well.

Liu (2009) projected Chinese mid-long term electricity demand through statistical method, the results have more than 80% resemblance with our findings (see Figure 6). Yang (2012) analyzed CO_2 emissions of Chinese electricity industry from 2005 to 2020 through system dynamics modeling, see Figure 7, we almost derived the same results. And long-term projections of future CO_2 emissions and electricity generation structure are comparable to other institution's reports (Bloomberg New Energy Finance, 2013). All these comparisons indirectly provide evidences for the validity of our model.

Extreme condition test aims to check whether the model outcomes still make sense under extreme conditions. For example, if the GDP growth rate in China is extremely low (negative), clean electricity sources can meet all the demand, required coal electricity capacity is 0. As a result, the total annual CO_2 emissions will decline gradually, stabilizing at a very low level in the end because of emissions from gas power plants. If the GDP growth rate is extremely high, the total annual CO_2 emissions will be out of control, increasing exponentially.

Extreme tests on other parameters also prove that this model is robust as results derived from it under extreme conditions are still meaningful.

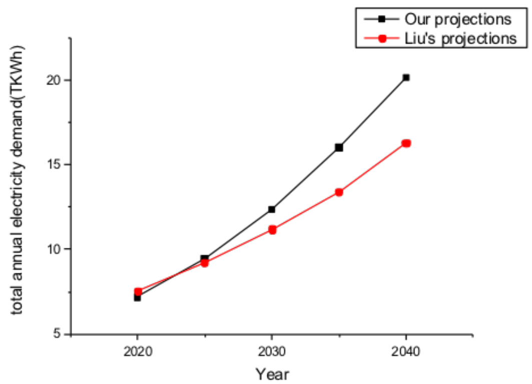

Figure 6: Comparison of total annual electricity demand projections.

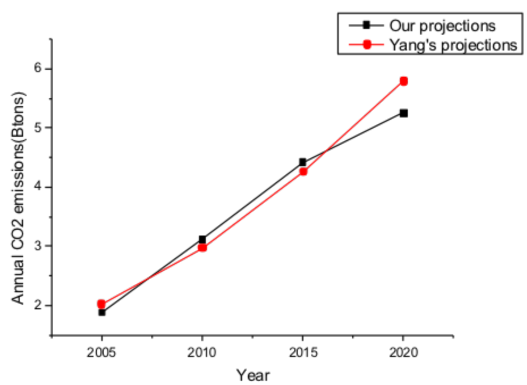

Figure 7: Comparison of annual CO_2 emissions projections.

4 Sensitivity test

In order to test the influence of relatively small changes in different factors on the key performance indicator, total annual CO_2 emissions from power industry, sensitivity tests on some main factors are performed.

Figure 8 and Figure 9 show the results of sensitivity analysis of the following four parameters: industrial rate, solar and wind capacity growth rate, electricity consumption intensity in secondary industry and CO_2 emission intensity without CCS. Their values are increased or decreased by 10% respectively.

From the results, it is able to say that the model is numerically sensitive but not behaviorally sensitive on these factors. Among them, changes in electricity consumption intensity of secondary industry have the largest impact on total annual CO_2 emissions. 10% decrease of the electricity consumption intensity results in a large drop in total CO_2 emissions. CO_2 emission intensity of coal-fired power plants without CCS and industrial rate also significantly affect total annual CO_2 emissions. Therefore, these factors are probably the leverage points where policies can based on.

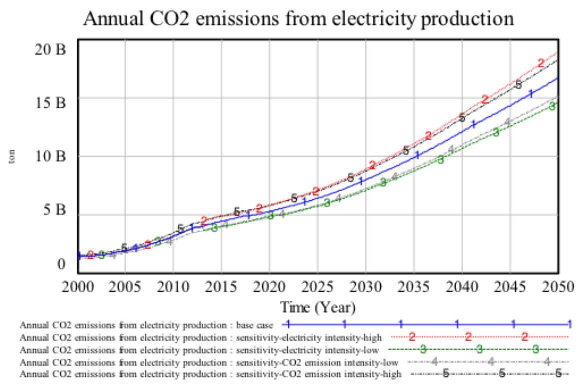

Figure 8: Sensitivity test for electricity intensity and CO_2 emission intensity.

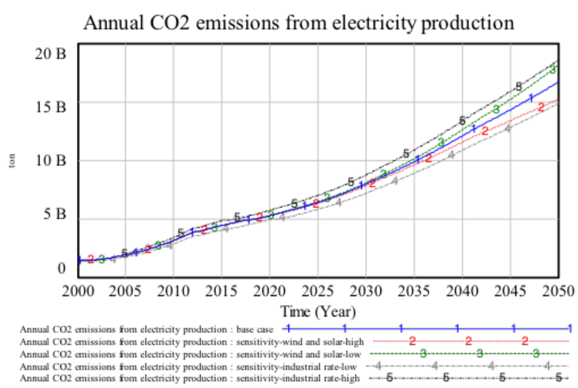

Figure 9: Sensitivity test for wind/solar growth rate and industrialization rate.

5 Base case simulation results

The base case is a hypothesized scenario based on default values and assumptions. The main assumptions for this study are: (i) There is no electricity supply shortage, all electricity demand can be met by supply. (ii) All electricity generated by renewable sources can be eventually utilized. (iii) The goal for emission reduction in electric power industry is consistent with overall target, hence it is required to contribute the same amount as other sources.

According to the thirteenth five-year plan, the expected GDP growth rate for the next five years is at least 6.5% (State Council of the People's Republic of China, 2016). The long-term projections towards GDP growth rates till 2050 are shown in Table 1.

Figure 10 displays the base case results of CO_2 emission intensity. Chinese government will be very close to its target with regard to CO_2 emission intensity in base case. CO_2 emission intensity will experience a steady downward trend, from about 1.1kg/CNY in 2005 to 0.53kg/CNY in 2030. It declines by 52% by 2030 from the 2005 level. This trend is due to the development of clean electricity sources and the declining electricity consumption intensity of industry.

Table 1: GDP growth rate projections.

Year	2015-2030	2030-2040	2040-2050
Growth rate projections	6.5%	6%	5.5%

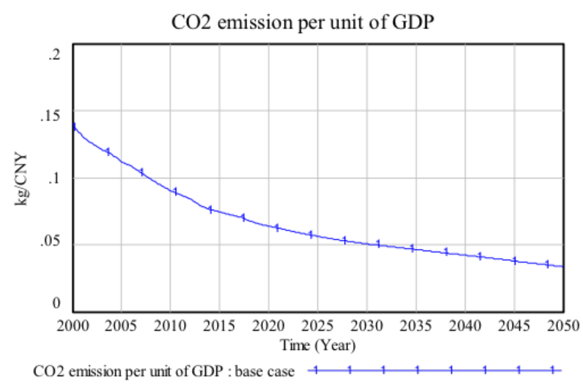

Figure 10: Base case simulation result of CO_2 emissions per unit of GDP.

However, in terms of annual CO_2 emissions, the situation is not that optimistic. China can not realize its promise on total CO_2 emissions in the base case scenario. Contrary to the expectation, the annual CO_2 emissions will not reach the summit by 2030. Instead it will keep on growing afterwards. Figure 11 illustrates that the annual CO_2 emissions will reach 8.9 billion tons in 2030, finally climbing to 18.03 billion tons in 2050. The main driving force is the rapid growth of electricity demand. Fueled by the rising GDP, the gross electricity demand is constantly rising along with total CO_2 emissions (see Figure 12). In addition, the relatively slow development of clean energy sources is another cause for the unruly total CO_2 emissions. Figure 13 shows that the fraction of coal electricity will decline to 58% in 2030 from about 69% at present under the current clean energy development plan. Meanwhile the share of clean electricity sources will raise. As one of the most important components in clean electricity sources, solar and wind electricity will comprise around 11% of the whole electricity supply in 2030. This proportion is still very small if compared to developed countries. For instance, wind power produced 42.1% of Denmark's total electricity consumption in 2015. So, there is considerable development potential for renewables in China.

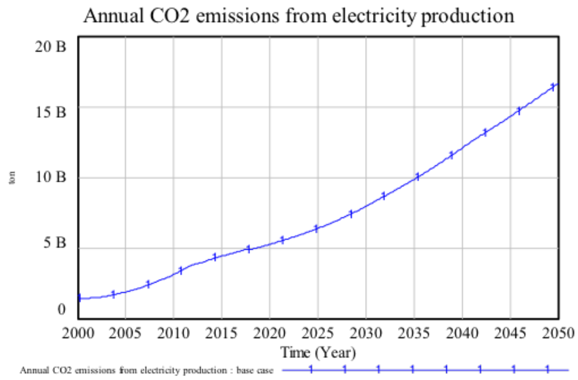

Figure 11: Base case simulation result of annual CO_2 emissions.

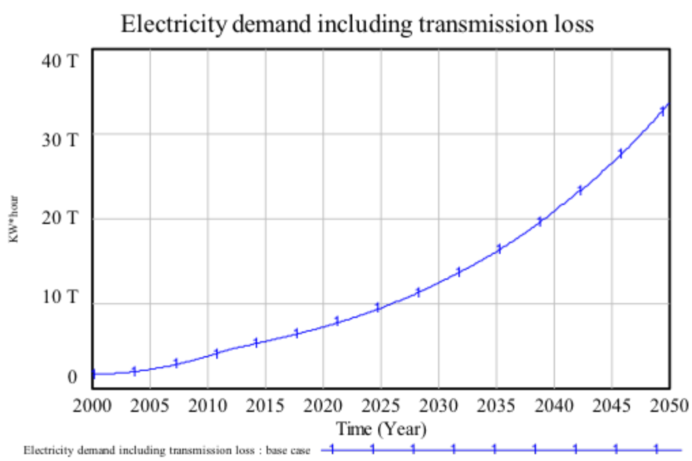

Figure 12: Base case simulation result of gross electricity demand including transmission rate.

To sum up, the status quo simulation confirmed that China is unable to satisfy its target within current policies. The total annual CO_2 emissions will not peak by 2030 in the base case scenario, instead it will keep increasing. To some extent, restriction on CO_2 emissions means limiting GDP growth. As Figure 14 suggests, only if the average GDP growth rate decline to 3.5%, then it is possible for the total CO_2 emissions to meet the commitment with current measures. Surprisingly, the seems impossible goal, to curtail CO_2 emission intensity by more than 60% by 2030 compared to the 2005 level, turns out to be easier to realize. In the base case, CO_2 emission intensity will decline by more than 50%, which is very close to the target. Therefore, the main difficulty is how to effectively curb the total annual CO_2 emissions, on which the current measures are not enough.

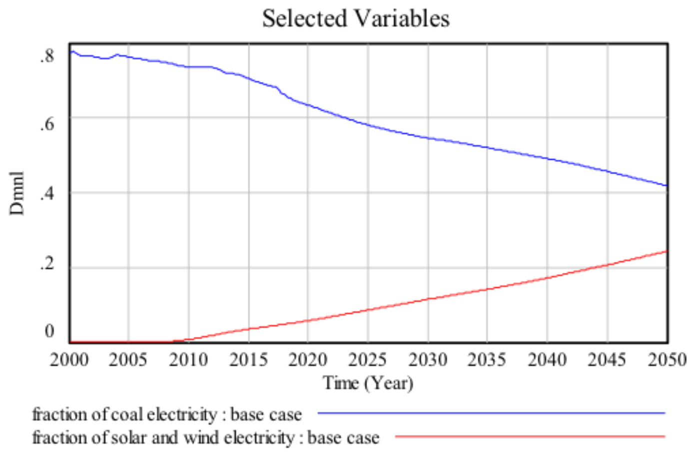

Figure 13: Base case simulation result of fractions of different electricity sources.

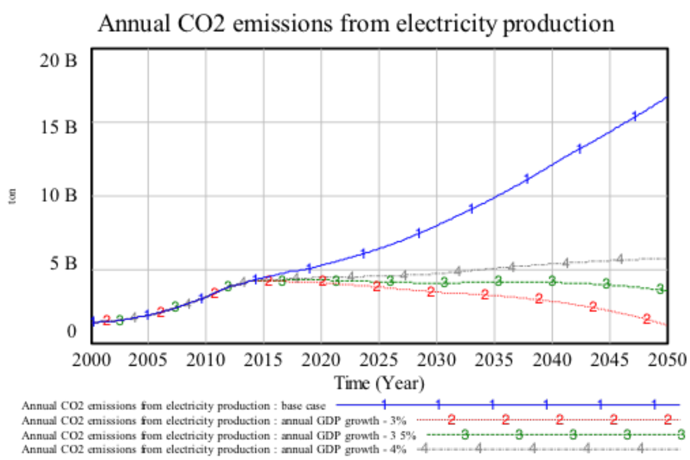

Figure 14: Base case simulation result of GDP development space.

6 Policy analysis

The base case analysis confirmed the current plan and policies are not enough to support the promise on emission reduction. Thereby it is essential to further seek some appropriate policies to help the country in reaching the targets.

The status quo simulation identified the main problem is how to effectively reduce the annual CO_2 emissions. In order to peak around 2030, ensuring that annual CO_2 emissions are not rising from 2030 onward is a key point. Thus, controlling CO_2 emissions after 2030 is especially important, and it is also the timeframe that policies should focus on. Based on the results of sensitivity test and base case test, the following policies were formulated. Figure 15 and Figure 16 present the results of these policies.

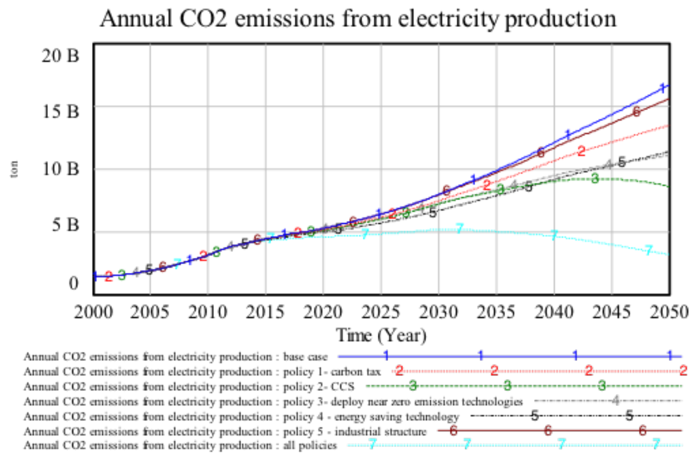

Figure 15: Policy effect on annual CO_2 emissions from electricity production.

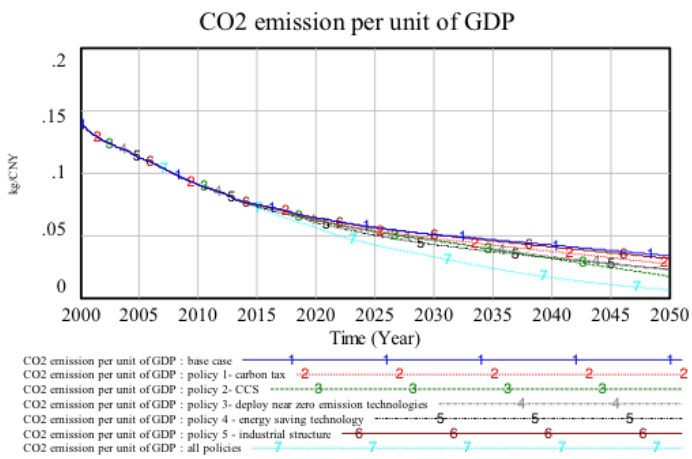

Figure 16: Policy effect on CO_2 emissions per unit of GDP from electricity production.

(1) Policy 1: Introduce carbon tax

Carbon tax is a common policy tool to regulate carbon emissions (Fiddaman, 2002). Many countries all over the world have enacted policies to levy carbon tax, such as western European countries. This policy has been put on the agenda in China, as the government has announced that the country will begin implementing a national cap-and-trade system for greenhouse gas emissions in 2017 (Davis & Davenport, 2015).

Implementation of carbon tax will effectively mitigate the CO_2 emissions (Wang, Ge & Yan, 2011). The influences of carbon tax mainly come from two aspects. On one hand, carbon tax will weaken the price advantage of fossil energy, such as coal. The attractiveness of renewable energy sources, such as wind and solar, will be reinforced. On the other hand, enactment of carbon tax will motivate companies to put more efforts on energy saving techniques. This means it will accelerate the decrease of electricity consumption intensity in industry.

The effect of this policy is also related with the carbon tax rate. Higher price of carbon results in a larger impact. It is believed that China's carbon tax rate would initiate from a low point so as not to bring forth too much influence on China's economy (Wang, Ge & Yan, 2011). For this study, it is assumed that carbon tax policy will increase the annual growth rate of solar and wind capacity by 1% to 3% and the decrease of annual electricity intensity of industry will be accelerated by 0.3% to 0.9%. On around 2030, the tax rate will be gradually raised to a high level.

The carbon tax policy does have effects on the key performance indicators. The increase of annual CO_2 emissions slows down slightly, but CO_2 emissions are still growing. While CO_2 emission intensity is very close to the objective.

(2) Policy 2: Implement CCS system in coal-fired power plants

Carbon dioxide capture and storage (CCS) technology is a widely accepted technology to tackle the carbon emissions problems in traditional power plants. CO_2 emissions in conventional power plants could be reduced by 80-90% with CCS facilities (Metz, Davidson, De Coninck, Loos, & Meyer, 2005). Although CCS technology is not an economically wise choice at present, advancement in technology and drop in cost can be expected with engineering experiences accumulating. So introducing CCS system into coal-fired power plants is a great opportunity for China.

This policy raises the ratio of coal-fired power plants with CCS system to 70% at 2050, and the CO_2 capture rate is set to grow gradually to 80% at 2050. As Figure 15 and Figure 16 exhibit, the impact on emission reduction is very significant. The turning point of total CO_2 emissions appears around 2040, which is too late compared to the target. CO_2 emissions intensity also experience an important fall from the base case.

(3) Policy 3: Deploy near-zero technologies for coal

Apart from installing CCS system in coal-fired power plants, carbon emission reduction in power plants without CCS system is also important. Several readily deployable technologies available to reduce CO_2 emissions from coal-fired power plants exist. One option is the ultra-supercritical boiler: its thermal efficiency is 30% higher than old and small units, which results in potential carbon emission reductions of up to 30% at best (ABB, 2011). IGCC plants are representative for highly efficient power plants, so they could contribute to emission reductions.

By applying these technologies, the emission intensity of traditional coal-fired power plants could gradually decline. It is assumed that the emission intensity of coal-fired power plants can be reduced eventually by 30% till 2050. The result is shown as line 4 in Figure 15, the rapid growth of total CO_2 emissions is alleviated effectively in the end of the period, but there is no evidence that the total emissions have reached the peak.

(4) Policy 4: Energy saving technology

Although a 0.5% annual decrease in electricity consumption intensity of the secondary industry has been assumed in the base case, there is larger room for energy efficiency increase in Chinese industry. The average energy intensity of Chinese industry is more than twice the intensity of European industry (ABB, 2011). With current available technology, it is feasible to achieve an extra 1% annual reduction. The result of this policy is quite similar to that of policy 3. CO_2 emission intensity of GDP is satisfying while the growth of annual CO_2 emissions would not stop.

(5) Policy 5: Improve industrial structure

In China, the secondary industry accounts for around 44% of total GDP. This amount is much smaller in developed countries, such as the USA and Western European countries, where the tertiary industry holds a share of more than 70%. As expected, the fraction of Chinese secondary industry is likely to shrink with the surge of the tertiary industry. As the tertiary industry is much less energy intensive, so the decreasing fraction of the secondary industry might result in emission reduction.

If the share of secondary industry declines to 35% in 2050, the impact on carbon emission reduction can be seen as line 6 in Figure 15 and Figure 16. The effectiveness of this policy is limited, which is the worst among five policies.

(6) All policies

As stated, none of the single policy is strong enough to meet the emission reduction targets. So the effect of combining all policies is tested. It is obvious that the effect is the greatest if all policies are active. A clear turning point of total CO_2 emissions at 2030 occurs. The total CO_2 emissions falls steadily from 2030 on, it almost goes back to the 2005 emission level by 2050. In addition, the CO_2 emission intensity is reduced by 70% by 2030 compared to the 2005 level. Therefore, by applying all policies, China is able to reach its promise on carbon emission reduction.

In this case, the percentage of clean electricity sources increase to over 80% by 2050, it means that coal electricity's proportion will fall to around 20% at that time. Half of the clean electricity supply (40%) will be contributed by solar and wind energy. A detailed distribution of electricity supply is given in Table 2.

Table 2: Structure of electricity supply.

	2015	2030	2050
Coal electricity	68.6%	52.7%	18.9%
Clean electricity	31.4%	47.3%	81.1%
Electricity from wind and solar	3.8%	12.6%	37.4%

The coal power capacity required to ensure electricity security can also be obtained from the simulation results. Due to excessive capacity status quo, current capacity is able to meet the demand until 2018. After that, a slight upward trend is followed. The coal electricity capacity will finally stabilize at 1.1 million MW by 2035. It implies that from 2035 onwards, the rising part of overall electricity demand can be fully covered by the growth of clean electricity.

7 Policy testing under uncertainty

We have tested the effectiveness of these policies across a large uncertainty space as in (Kővári & Pruyt, 2014). A thousand simulation runs based on Latin hypercube sampling were performed to test each policy. The uncertainty ranges for parameters are attached in the Appendix. Among these parameters, GDP growth rate is exceptional since it has a large influence on CO_2 emissions. Hence, its impact will be discussed separately.

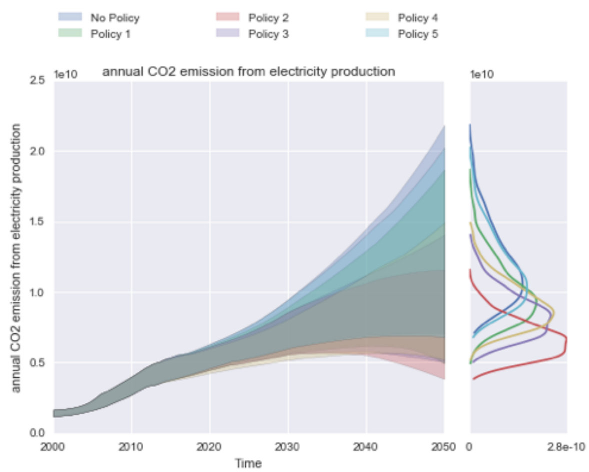

Figure 17: Envelops and kernel density estimates of annual CO_2 emissions of single policy situations.

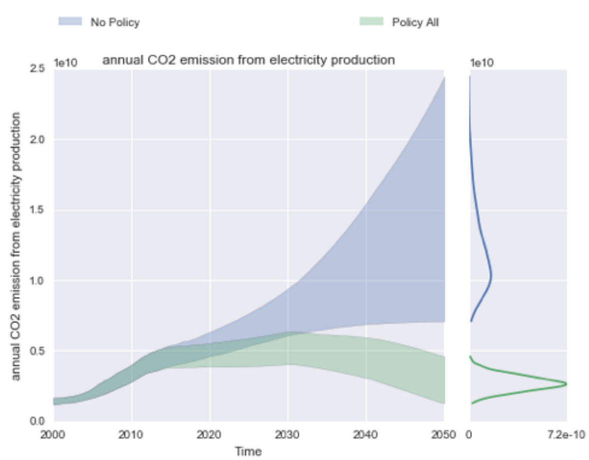

Figure 18: Envelops and kernel density estimates of annual CO_2 emissions of all policies situation.

The results of the policy simulations under uncertainty, excluding GDP, are displayed in Figure 17 to Figure 19, each figure consists of visual ensemble inspection (left) and Kernel density estimation (right). Figure 17 contrasts the envelopes of annual CO_2 emissions from electricity production in the 'no policy' and separate policy scenarios. The outcome indicates that annual CO_2 emissions are spread out without policy intervention. It confirms that policy 2, installing CCS systems, has the most significant impact on reducing annual CO_2 emissions.

Whereas, no single policy allows for reversing the further increase in annual CO_2 emissions under deep uncertainty.

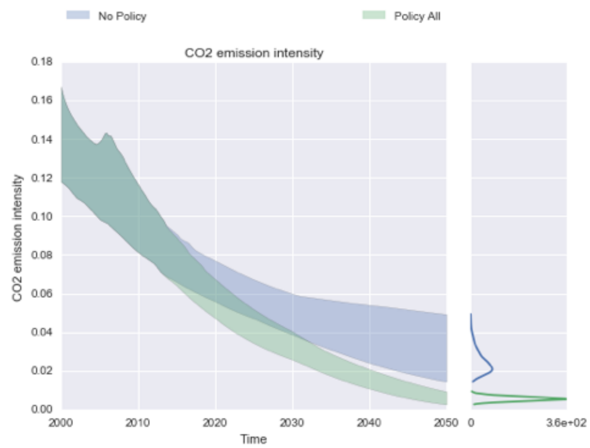

Figure 19: Envelops and kernel density estimates of CO_2 emissions intensity of all policies situation.

Nonetheless, the performance of the combination of all policies is much more impressive (see Figure 18). This combined policy cluster is effective under all scenarios. When the conditions are optimal, the annual CO_2 emissions will grow slowly till 2030, then decrease substantially to the 2000 level by 2050. Even in the worst situation, the goal to reach the peak in 2030 can be realized and annual CO_2 emissions will fall down gradually afterwards. Figure 19 shows that a reduction of 60% on CO_2 emission intensity by 2030 from the 2005 level is feasible.

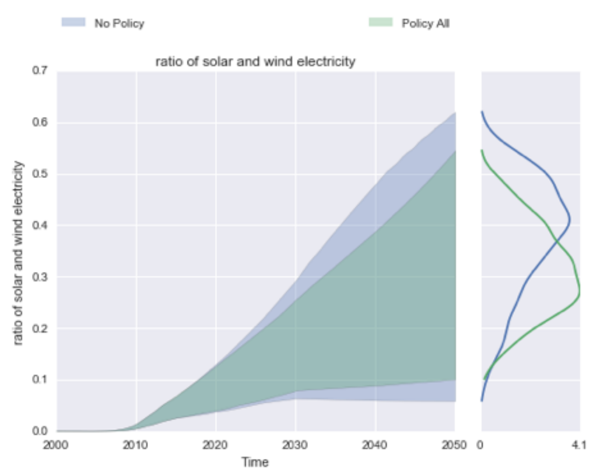

Figure 20: Envelops and kernel density estimates of fraction of wind and solar power of all policies situation.

Under uncertain situation, the development of renewables and other electricity sources has diverse possibilities. Shown in Figure 20, enacting all policies does not necessarily raise the fraction of wind and solar energy, compared to the base case.

Furthermore, uncertainties of future GDP growth rates are studied. As known, if GDP growth rates are below expectation, then less electricity supply is required and less CO_2 emission is expected, the emission reduction targets become easier. But if GDP growth rates exceed expectation, the current combination of policies might not perform effectively. It is worthwhile to investigate the behaviors of the model in situations with higher GDP growth rates.

Figure 21 shows the variations of annual CO_2 emissions with average GDP growth rates from 6.5% to 9%. The results indicate that this policy set can ensure the success of emission reduction despite the uncertainties of other parameters when the average GDP growth rate is below 7%. Even if the average GDP growth rate is as high as 9%, this policy cluster might be sufficient if other uncertain parameters are optimal.

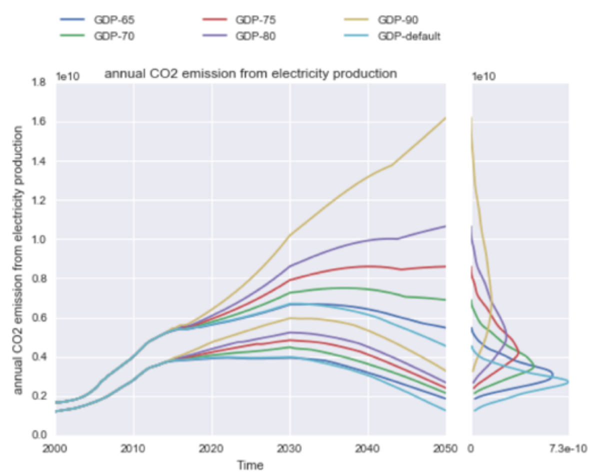

Figure 21: Upper, lower limits and kernel density estimates of annual CO_2 emissions with different GDP growth rates.

8 Conclusion

In this paper, we used a system dynamics model to investigate China's possibility of realizing its emission reduction ambitions. Several policies to help China in this process were tested.

The simulation results of the base case suggest that China cannot fulfill its promise within the current development proposal. The most significant problem is that the annual CO_2 emissions will not stop growing by 2030. Although carbon intensity of GDP falls substantially, the decrease is still not fast enough to meet the 60% reduction target by 2030.

Five different policies to tackle the existing problems were tested. These policies are: (i) levying carbon tax, (ii) implementing CCS system in coal-fired power plants, (iii) deploying near zero emission technologies for coal-fired power plants, (iv) stimulating technology advancement in energy saving, (v) improving industrial structure. Among them, implementing CCS is the most effective, since it successfully drives down the annual CO_2 emissions. However, the turning point occurs too late, although the carbon intensity can meet the expectation. No single policy has enough power to accomplish the overall goal. Based on these results, it can be inferred that the goal of peaking annual CO_2 emissions by 2030 is much harder than the target to cut down carbon intensity of GDP by 60%, though 60% reduction sounds very ambitious. The fact supporting this argument is that the total electricity consumption will double from 2030 to 2050. Thus, greater efforts are required to stabilize the total CO_2 emissions.

China's emission reduction ambition can only be realized if all policies are implemented and accomplished. A clear turning point of annual CO_2 emissions can be witnessed in 2030. The total emissions will decline to 2005 level in 2050. And the carbon intensity will drop by around 70% in 2030 from 2005 level. Uncertainty analysis confirmed this conclusion. The government is able to keep the promise on emission reduction even under the worst conditions within this policy set if GDP grows as expected. And the policy set is strong enough to stand an average growth rate up to 7% in the uncertain context. Higher growth rate is also possible when other parameters are optimal.

As for the development of renewables and the structure of Chinese electricity supply, high fractions of renewables and clean electricity are expected in the future according to the simulation of all policies combinations. However, simulation under uncertainty suggests that the possible ranges are quite broad. They are depending on the realization extent of CCS systems and how the Chinese government decides to react on external pressure. If CCS systems are highly successful and the government does not take active measures, the fraction of renewables will grow slowly. Otherwise, fast increase of renewables and other clean energy sources are required.

This model corresponds to a perfect system, assuming all policies mentioned are executed and fully achieved. While in reality, resistances could be expected, 100% achievement is not always realistic. The meaning of such an ideal scenario is that it illustrates the potential of emission reduction with currently available technologies. It provides policy makers with more information about the future trends and the effectiveness of different policies.

Although uncertainty of the parameters and structures are considered in this study, deviations may still exist because of inaccurate projections of future uncertainty ranges. The future can not be precisely predicted. Whereas, the overall trends should be independent from individual data.

To seize the largest emission source, this work only focuses on CO_2 emissions from electric power industry. Future research may enrich the picture by modelling other industries with intensive CO_2 emissions or building system dynamics models from an overall perspective. In addition, cost and benefit analysis for different electricity sources, carbon trading market and CCS technology might add value to this study. Diving more into economic side of climate change is likely to derive more interesting and valuable insights.

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Appendix

1 Overview of the simulation model

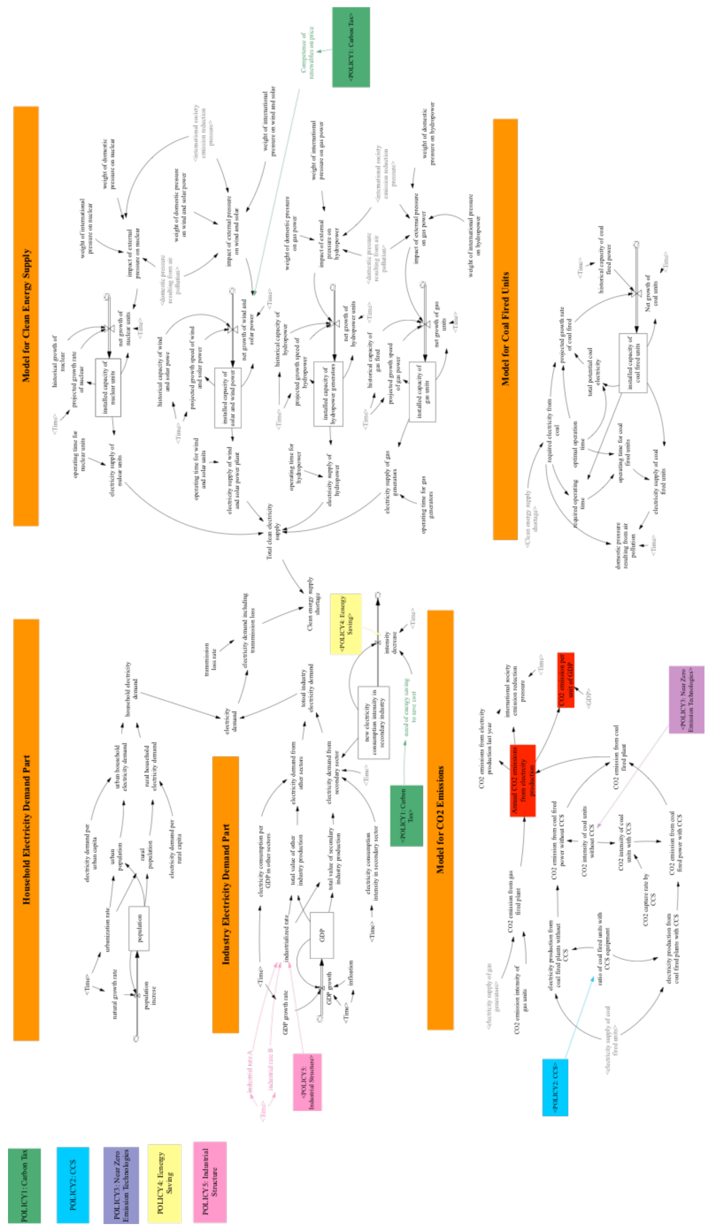

Figure 22: Overview of the simulation model.

2 Parameters for Uncertainty Analysis

Table 3: Constant parameters and calibration intervals used for Uncertainty Analysis.

Parameter	Units	Value	Interval	Sources
efficient operating time for wind and solar units	hour	1900	(1500,3500)	(China Electricity Council, 2015)
Electricity demand per rural capita	KW*hour/Person	200	(150,600)	(China Electricity Council, 2015)
Electricity demand per urban capita	KW*hour/Person	600	(400,1000)	(China Electricity Council, 2015)
Operating time for gas generators	hour	4700	(2000,6000)	(China Electricity Council, 2015)
Operating time for hydropower	hour	3700	(2500,4500)	(China Electricity Council, 2015)
Operating time for nuclear units	hour	7500	(6000,8000)	(China Electricity Council, 2015)
Optimal operation time	hour	5500	(5500,6500)	(China Electricity Council, 2015)
Transmission loss rate	Dmnl	0.06	(0.04,0.1)	(China Electricity Council, 2015)
Effect weight of international society emission reduction pressure on wind and solar	Dmnl	0.5	(0,2)	Assumed
Impact weight of domestic pressure on wind and solar power	Dmnl	0.5	(0,2)	Assumed
Impact weight of domestic pressure on hydropower	Dmnl	0.2	(0,1)	Assumed
Impact weight of domestic pressure on nuclear	Dmnl	0.3	(0,1)	Assumed
Impact weight of domestic pressure on gas power	Dmnl	0.5	(0,2)	Assumed