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Capturing the co-benefits of energy efficiency in China — A perspective from the water-energy nexus

Yuanchun Zhou[a,b], Mengdie Ma[a], Fanbin Kong[b], Ke Wang[c], Jun Bi[a,*]

[a] State Key Laboratory of Pollution Control and Resource Reuse, School of Environment, Nanjing University, Nanjing 210023, PR China
[b] School of Government, Nanjing University, Nanjing 210023, PR China
[c] School of Environment and Natural Resources, Renmin University of China, Beijing 100872, PR China

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ABSTRACT

To address air pollution and control greenhouse gas emissions, China has been implementing a number of national energy policies. This paper assesses the environmental and water saving co-benefit of long-run energy efficiency improvement based on a recursive multi-sectoral dynamic CGE model. A 3% and 5% energy efficiency improvement, based on using different types of energy, is imposed on all of the 47 production sectors in China. Our results show that more water will be used for energy production in the future because of the increase in energy production. Energy efficiency improvement can bring significant water saving co-benefits in addition to air pollution reduction. Energy efficiency improvements can also help the government to achieve the "3 Red Lines" goal. Such co-benefits have mostly been ignored by the government and energy production plants in their plans or cost-benefit analyses. Our study provides a new perspective for decision makers seeking to balance energy and water constraints.

1. Introduction

Energy consumption-related air pollution and greenhouse gas (GHG) mitigation is a significant issue in China today, driving energy policy reform in China in recent years (Gao et al., 2016; Meng et al., 2015; Wang et al., 2016). From 2000 to 2015, China's primary energy consumption increased by a factor of 1.9, while domestic energy production increased by 160 percent (National Bureau of Statistics of the People's Republic of China, 2016). Hence, the Chinese government has taken measures to control or slow down the growth of energy consumption. Energy efficiency improvement has become one of the core objectives of China's energy policy reform (Li et al., 2016; Liu et al., 2017). The main governmental policies have emphasized its importance. For example, the 10th, 11th, 12th and 13th Five Year Plans all established an ambitious goal of improving energy efficiency. The air pollution prevention and control action plan (State Council, 2013) and China's nationally determined contributions (NDCs) (National Development and Reform Commission, 2015) similarly exemplified the importance of energy efficiency improvement. According to the world energy research group of China Outlook, "energy efficiency in China should [not only] be the focus of policy oriented, industrial strategy and consumption patterns change but also a key indicator of energy transformation" (Research Group of World Energy China Outlook, 2015). Energy efficiency improvement has been broadly regarded as creating multiple benefits in a cost-effective manner, and has been widely employed. In addition to providing energy savings, air pollution control and GHG emission reduction, energy efficiency can also bring various macroeconomic benefits, increased energy security, and health benefits (IEA, 2014). The computable general equilibrium (CGE) and macroeconometric models are the main methods used to assess the macroeconomic and energy impacts of energy efficiency measures (IEA, 2014; Lin and Du, 2015; Lu et al., 2017). Macroeconometric models are economy-wide models based on estimates of historical relationships, including the latent variable approach (Shao et al., 2014), the DEA approach (Gale and Joseph, 2006; Lin and Liu, 2012; Pacudan and Guzman, 2002; Xu et al., 2017), and the LMDI method (Ang, 2006; Ang et al., 1998; Zhang et al., 2016c). It is hard to apply these models to study structural changes and interactions between different sectors. CGE models are considered to be beneficial in that they provide information to simulate the response of the full economy to certain policy scenarios, such as a carbon tax (Dong et al., 2015; Dong et al., 2017). It can identify subtle linkages between different economic sectors and explicitly describe the response of economic agents to energy efficiency change. Hence, CGE models have already been used to model the energy efficiency impact worldwide (Koesler et al., 2016; Lu et al., 2017; Sorrell et al., 2009; Yu et al., 2015).

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* Corresponding author at: 163 Xianlin Avenue, Nanjing University, Nanjing, China, 210023. Tel/Fax: +86-25-89680566.
E-mail addresses: zhouych11@nju.edu.cn (Y. Zhou), wangkert@ruc.edu.cn (K. Wang), jbi@nju.edu.cn (J. Bi).

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What's more, CGE has also been widely used to study the co-benefit effect of different policies. Some studies have used CGE model to analyze the implications of climate and energy saving policies on air pollutants (Bollen, 2015; Cheng et al., 2015; Dong et al., 2015) and how they can bring about health benefits (Jensen et al., 2013; Keogh-Brown et al., 2012; Xie et al., 2016) in developed and developing countries. Besides energy and climate policies, other environmental policy co-benefits were also evaluated utilizing the CGE model, including an environmental tax (Xu and Masui, 2009). Babatunde et al. (2017) has reviewed the application of CGE to climate change mitigation policy, and found that energy efficiency and co-benefit of mitigation measures are fairly represented (Babatunde et al., 2017).

The rebound effect is an important aspect of energy efficiency studies (Liang et al., 2009; Lu et al., 2017; Turner, 2013). Moreover, the rebound effect study of energy field can contribute to a general framework in analyzing other environmental policies (Vivanco et al., 2016), which means incorporating broader efficiency changes as well as energy. The idea of rebound effect is that energy efficiency improvements may lead to additional energy consumption due to reduced prices of energy services caused by the improvement; anticipated energy savings from improved energy efficiency may thus be partly or wholly offset or even surpassed (Greening et al., 2000; Turner and Hanley, 2011). When energy efficiency improves, demand for energy input in the production will decrease, and the demand curve will move inward. But in the long-run, firms may further optimize production cost by adjusting their capital stock, which means the advantage of energy efficiency improvement may be offset by a lower capital price. However, existing studies show that the rebound effect varies widely at the economy-wide and department levels in the long and short run, from negative to more than 100% (Dimitropoulos, 2007; Lu et al., 2017; Sorrell et al., 2009).

In addition to the benefits mentioned above, the water-energy nexus provides a new perspective for understanding the impact of energy efficiency improvement. The energy consumed every day has considerable direct and indirect effects on water resources (Behren et al., 2017; Fang and Chen, 2016; Huang et al., 2016; Sovacool and Sovacool, 2009; van Vliet et al., 2016; Zhang and Anadon, 2013; Zheng et al., 2016). Water is important for different energy production, such as coal mining and washing, gas and oil extraction and electricity generation (IEA, 2015; Mekonnen et al., 2016; Zheng et al., 2016). Water constraints have already impeded energy development in China, for example, by leading to the abandonment of energy production projects in water shortage areas (Yang et al., 2013). Some regions such as Shandong and Shanxi are facing huge water stress while also producing more energy compared with other regions (see Fig. 1). In addition, with both increasing energy and water demand, conflicts between water availability and energy sector demand have been anticipated in several studies in China (Green Peace, 2017, Gu et al., 2014; Liao et al., 2016). Under a 'business as usual' scenario, the energy sector's water use might exceed the Industrial Water Allowed on a national scale in China in 2035 (Qin et al., 2015).

The water-energy nexus is supported by a rapidly growing evidence base, providing knowledge to inform stakeholders and decision-makers about the relationships and trade-offs between different sectors (Allan et al., 2015; Howarth and Monasterolo, 2016, Howells et al., 2013). However, these two resources are often poorly integrated and have been managed separately (Holland et al., 2015; Yumkella and Yillia, 2015). Over the last decade, many papers and policy reports have examined the nexus at different scales (Bergendahl et al., 2018; Fang and Chen, 2016; Zhang et al., 2016a). Inventory analysis (Cai et al., 2014; Guo et al., 2017; Liao et al., 2016; Zhang et al., 2014) and input–output analysis (Fang and Chen, 2016; Feng et al., 2014; Jin et al., 2017) are the main methods employed to quantify water demand for energy production. In addition to describing the physical linkage between different sectors (Acheampong et al., 2016; Chang et al., 2016), assessing the spillover effect of energy policies on water resources is also important, including the energy price (Gulati et al., 2013; Zhou et al., 2016), technology innovation (Allouche, 2015), and resource use efficiency (Bartos and Chester, 2014; Ringler et al., 2013). The main method to perform the assessment is scenario analysis based upon energy projections combined with water use inventories. Some studies just use energy projection results of other researches to assess the impact, such as IEA (Cai et al., 2014; Qin et al., 2015; Zhang and Anadon, 2013) and WWF (Liao et al., 2016). Other researchers have developed energy models to assess the impact of energy policies, such as CGE (Zhou et al., 2016), LEAP (Dale et al., 2015; Howells et al., 2013), and TIMES (Huang et al., 2016).

A systematic method for estimating water requirements for energy production is important to support management of both energy and water resources. In this paper, a water module is integrated into a CGE model to integrate China's energy and water system and to assess the co-benefit of energy efficiency improvement from 2015 to 2030. This study should provide some new and insightful implications for China's sustainable development, especially for the reasonable utilization of water and energy resources.

2. Material and methods

2.1. Research scope

In our study, only water withdrawal during energy production process was evaluated. Water withdrawal refers to the diversion of water from one source to another without loss, which is different from water consumption. Energy production in this study refers to primary energy extraction, processing (such as washing, refining), and electricity generation from different fuels, including coal, natural gas, nuclear, hydro, wind, and solar. Our study focuses on the impact on freshwater, so sea water use was not accounted for. Wind and solar PV operations need negligible water and were not considered in this study (McMahon and Price, 2011). Hydroelectric power generation does not withdrawal water or divert water flow and was also not considered in our study. Water withdrawal for nuclear power was not accounted because most of nuclear fuel is not produced domestically (World Nuclear Association, 2009) and all nuclear power plants in China use seawater for cooling (Zhang et al., 2016a). Water withdrawal for bioenergy production is not considered because the calculating methods and scope may bring a large amount of uncertainty (Cai et al., 2014).

Cooling technology adopted by power plants has an important influence on water withdrawal. The main cooling technologies in China are once-through cooling, recirculating cooling and air cooling (Macknick et al., 2011; Zhang et al., 2016a). Once-through cooling systems have much lower water consumption ratio than recirculating cooling systems. Water was extracted from nearby water body and discharged back to the same water body after cooling process. Water extracted by recirculating cooling systems was mostly evaporated out of the cooling tower. Air cooling has minimal water withdrawal and consumption compared with other two cooling systems (Macknick et al., 2011; Qin et al., 2015; Zhang et al., 2014). These three types of cooling systems were used in our study (Zhang et al., 2016a; Zhou et al., 2016).

Water withdrawal for energy production was calculated as following:

$$\mathrm{W}=\sum_{1}^{n}\sum_{1}^{k} A_{i,m}\times E_{i,m} \tag{1}$$

where i indicates the fuel types from 1 to n and m designates different cooling types. W is water withdrawal of total energy production, $\mathrm{A_{i,m}}$ is water withdrawal factor of energy i, and $\mathrm{E_{i,m}}$ is quantity of energy i produced.

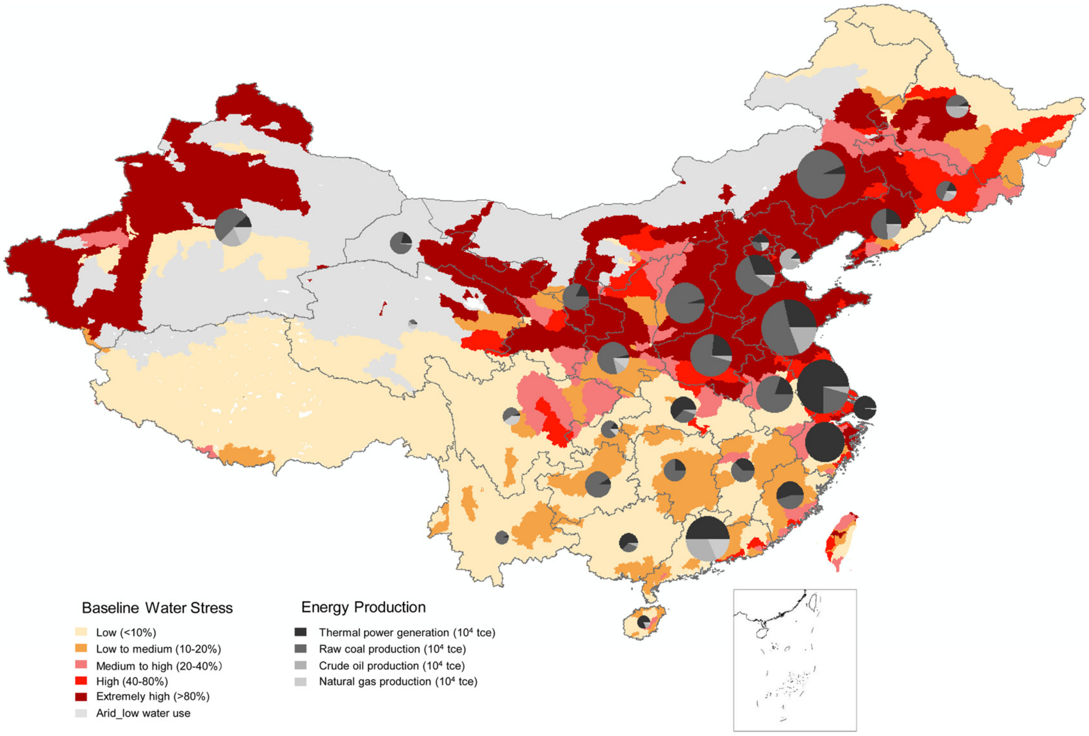

Fig. 1. Water stress and energy production in China.
Data Source: water stress was extracted from WRI's Aqueduct Global Maps 2.1 (Gassert et al., 2014), energy production data was extracted from China Energy Statistical Yearbook 2016 (Department of Energy Statistics et al., 2016).

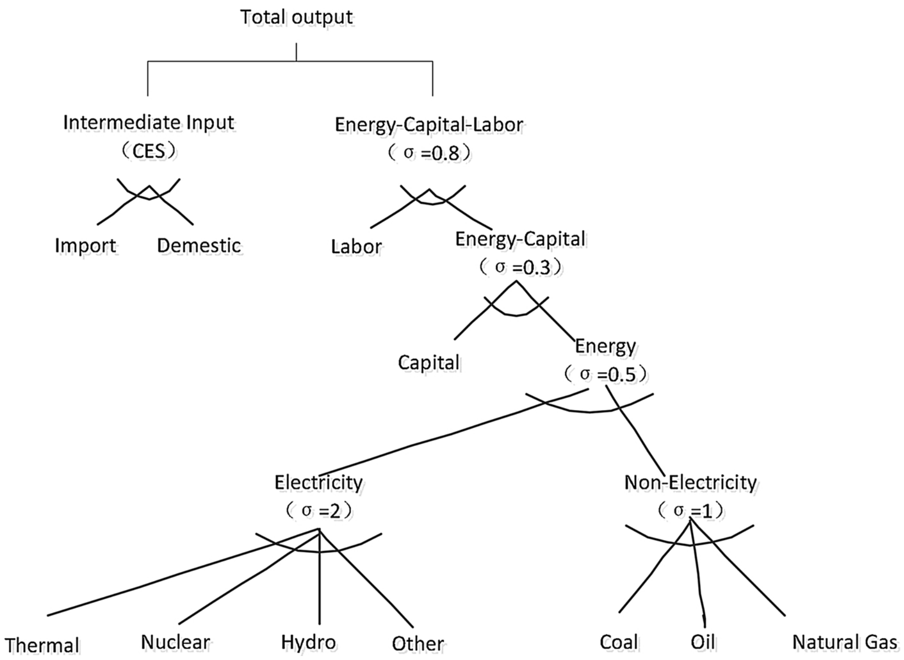

Fig. 2. Nested production structure of the CGE model.

2.2. CGE model

A recursive multi-sectoral dynamic and single region CGE model was developed to study the co-benefit of energy efficiency improvement on both energy and water resources from 2015 to 2030 (Wang et al., 2009; Zhou et al., 2016), which consists of three agents: government, households and enterprises. The behavior of each agent is mathematically characterized in different modules. The model includes a production module, a trade module, a price module, an income-expenditure module, an equilibrium module and a macroeconomic closure module. An international market that accepts exports from local production and supplies imports to the local commodity market completes the model of the economy. The local commodity market is a composite of domestically produced goods and imported goods. When all markets clear (supply equals demand), the model is said to have reached general equilibrium. To build a CGE model, we first choose the agents' behavioral functions and market clearing criteria, followed by calibration based on China's social accounting matrix (SAM) of 2012.

We introduce an energy module into the production structure, which is further disaggregated into different energy types. In the model, 47 sectors were considered, including 11 energy sectors and 36 non-energy sectors (refer to Supplementary Information). For each sector, a distinct commodity was assumed to be produced. The production activity of each sector is described by a nested constant elasticity of substitution (CES) production function. The producer decides the optimal volume of the factors and intermediate inputs to make the revenue maximization or cost minimization. At such a disaggregated level, the model allows us to trace how increased energy efficiency in one sector affects every other sector's production level, market demand and price, as well as sector-level energy use. The model is implemented in Mathematical Programming System for General Equilibrium under General Algebraic Modeling System (MPSGE/GAMS) (Rutherford, 1999). In our model, we impose energy efficiency improvement shocks on the specific energy goods.

The production activity of each sector is described by a nested CES production function (see Fig. 2). At the top level of nesting, the output of each sector is determined by a CES aggregation of non-energy intermediate commodities and an energy-capital-labor composite. The composite of non-energy inputs is in Leontief form. The energy-capital-labor composite is a CES aggregation of labor and an energy-capital composite where capital is substitutable with the composite of energy inputs. The composite of energy inputs is a CES aggregation of electricity and non-electricity. Electricity is further disaggregated into coal-fired electricity, nuclear electricity, hydropower, biomass and other electricity. The sector-specific elasticities of substitution (σ) in this model were drawn from another study (Wang et al., 2009). For international trade, the Armington assumption was used to solve the import and export differentiation between domestic and international markets (Armington, 1969).

In our dynamic model, labor force growth, capital accumulation and total factor technological progress are considered to describe inter-period adjustments. Between-periods labor supply is adjusted exogenously according to relevant research (Bao et al., 2013), as shown in Eq. (2):

$$L_t = L_{t-1}(1 + grl_t) \tag{2}$$

where L_t and L_{t-1} are the total labor force in periods t and t-1, respectively, and grl_t is the growth rate of the labor force in period t.

In the capital market, the total available capital is determined by the previous period’s capital stock and investment spending, capital accumulation is determined as shown in Eq. (3).

$$K_t = (1 - \delta)K_{t-1} + I_t \tag{3}$$

where K_t denotes the capital in period t; I_t denotes the total investment generated from previous-period investment; and δ is the depreciation rate of capital, set at 0.05 in this study (Bao et al., 2013). New capital is allocated to sectors based on their relative profit rates. Which means that capital has enough time to adjust and can flow to higher-return sectors.

2.3. Rebound effect

The rebound effect can be measured in many ways. In our study, we use the method from other studies to measure the rebound effect (Li et al., 2017; Wei, 2010) (see Table 1). The rebound effect can be derived as:

$$E_1 = E_0 \times (1 - \gamma) \tag{4}$$

Where E_0 denotes the initial market equilibrium quantity of energy, and E_1 denotes the theoretical quantity of energy with an energy efficiency improvement, γ is energy efficiency improvement rate.

E_2 denotes the actual market equilibrium quantity of energy with an energy efficiency parameter γ, then the rebound coefficient RE can be defined by:

$$\mathrm{RE} = \frac{E_2 - E_1}{E_0 - E_1} \tag{5}$$

2.4. Data sources

In this study, we updated the SAM 2007 used in our previous study (Zhou et al., 2016) and calculated China’s SAM 2012, based on the 2012 China input–output table. At the same time, the Statistical Yearbook of China and the Finance Yearbook of China were used for sector specification and agent behaviors matching. For the disaggregation of the energy sectors, main data are based on input-output tables and the energy balance tables. But the oil and gas extraction data was not separated, we divide it according to the cost shares from other studies (Aguiar et al., 2016). For electricity sectors, we used the share of different types of electricity extracted from the China Power Yearbook to separate data in Input-output table. Most of the substitution elasticity parameters that describe the combination of different inputs are taken from relevant studies (Tang et al., 2015; Wang et al., 2009; Zhou et al., 2016). A Biproportional Scaling Method (RAS Method) was used to balance Input–Output Table.

Since energy efficiency policy aimed at energy saving also produces benefits in terms of a reduction in pollutants, this study calculates emissions reduction for various pollutants. For simplicity, the paper assumes that air pollutants are from fossil fuels (coal, oil and natural gas), and emissions during the production process are not considered. For example, SO_2 emissions are computed in a linear relation (using exogenous emission factors) to the use of fossil fuels. The emission factors used in this study are extracted from other studies. CO_2 emissions factors for fossil fuel combustion are calibrated based on data from the IEA (IEA, 2016), while SO_2 and NO_x were from He et al. (He et al., 2015) (see Table 2).

In order to assess water withdrawal by energy production sector, we use water withdrawal factor of different energy types at national average level (see Table 3). The “3 Red Lines” goals require water use efficiency improvement, and water use intensity will decrease to 40 m^3/10000 Yuan in 2030. So we have also considered the technological progress of water use during the simulation process and assume the withdrawal factor will decrease 10% between different periods.

2.5. Scenario formulation

The analysis described in this study is based on a set of scenarios characterized by energy efficiency improvement in China. We assume that an exogenous, uniform energy efficiency improvement occurs in all productive sectors using energy, which results an economy-wide shock.

Table 1
Five rebound conditions.

	RE	Description
Backfire effect	> 1	Actual energy consumption amount would be larger than initial energy consumption.
Full rebound	= 1	No change of energy use even though there is technical progress.
Partial rebound	(0,1)	Energy saving caused by efficiency improvement would be partially offset by the rebound effect. Therefore, the actual quantity of energy would decrease compared with that in the initial state.
Zero rebound	= 0	Final actual energy consumption after technical improvement would be exactly equal to the one that should be.
Super-conservation	< 0	Actual energy efficiency improvement would be greater than theoretical energy efficiency improvement

Table 2
Emission factors of various energies.

	Coal	Oil	Natural gas
CO_2 (tC/TJ)	25.8–29.1	15.7–26.6	15.3
SO_2 (kg SO_2/kg)	0.0704	0.0018	–
NO_x (kg NOx/kg)	0.00908	0.01247	–

Table 3
Factors of water withdrawal for energy production in China.

Energy			Withdrawal
coal(m^3/t)	mining		1.16
	washing		0.26
oil(m^3/t)	exploitation		2.70
	refining		3.56
gas(m^3/TJ)	extraction		1.6
electricity(L/kwh)	thermal	once	101
		Recirculating	1.9
		air	0.4

Energy efficiency is defined as the amount of energy used to produce a unit of product (or service); increased energy efficiency implies using less energy to produce the same amount of product (or service). Therefore, a 5% energy efficiency improvement in our analysis is equivalent to using 5% less energy to produce the same amount of output at the sector level. We use 3% and 5% energy efficiency shocks as our simulation scenarios since many previous researchers have used these amounts (Lu et al., 2017; Turner and Hanley, 2011). Energy efficiency improvement was introduced in 2015, energy production during 2015–2030 was simulated based on our model and related water use was also assessed (see Table 4). The share of different cooling technologies adopted by the power plants is taken from another study (Zhang et al., 2016a), with once-through, recirculating and air cooling accounting for 45.0%, 41.0% and 14.0% respectively.

3. Results

3.1. Impact of energy efficiency improvement on energy sectors

On the national level, improving energy efficiency can indeed reduce China’s energy consumption and production according to our simulations. Energy production will continue to increase in the future, but the increased rate will be decreased due to energy efficiency improvement (see Fig. 3). Compared to the BAU scenario, total energy production is reduced from 14.4% (Ee-3%) to 21.3% (Ee-5%) due to energy efficiency improvement by 2030. Our results indicate that total primary energy consumption will increase by nearly 1.5 times in 2030 in all scenarios compared with 2015; however, compared with the BAU scenario, it will be reduced from 2% (Ee-3%) to 3.6% (Ee-5%) due to energy efficiency improvement. Compared with the BAU scenario, coal, oil and natural gas consumption all decreased in the energy efficiency scenarios, while consumption of non-fossil fuels increased by 4.7% to 11.7% in the Ee-3% and Ee-5% scenarios. Coal continues to dominate China's primary energy consumption, yet its share drops from 68.9% in 2012 to 52% in 2030, with 5% energy efficiency improvement. At the same time, coal, oil and natural gas imports all decreased due to energy efficiency improvement. It’s notable that, even with 5% energy efficiency improvement, energy demand in 2030 is a little higher than the goal set by the Chinese government, 6 billion tons of coal equivalent. The main reason is that our scenario only considers energy efficiency improvement and other policies are also needed to achieve the NDC goal.

Fig. 4 shows the rebound effect on different energy types with 5% efficiency improvement. The rebound effect is very different in China across different energy types. Compared with other energy, improving efficiency of using electricity has the smallest rebound while the natural gas gets the largest rebound effect. The rebound from improved efficiency of using gas supply can be as high as 66% in 2030. Results also show that the long run rebound effect is larger than the short run effect, maybe because firms may further optimize production cost by adjusting their capital stock (which means the advantage of energy efficiency improvement may be offset by a lower capital price).

3.2. Co-benefit analysis of energy efficiency improvement

When energy efficiency improves, all air pollutant emissions decrease considerably due to energy savings. The more energy efficiency improves, the greater the effect of air pollutants emission reduction, ranging from 6.5% to 7.3% for different pollutants. CO_2 emissions vary due to the emission factor, but the pollution reduction benefit is significant. SO_2 and NO_x show nearly the same reduction benefit as CO_2. It’s interesting that the benefit in 2030 is smaller than in 2020, the main reason being energy structure change, and increased use of non-fossil fuel (see Fig. 5).

With increasing energy production, water withdrawal for energy production also increased during the simulation period. If energy use occurs at current efficiency levels, water withdrawal for energy production will increase 66% by 2030. The electricity and heat sector are the main water users, accounting for 73% of total water withdrawn for energy production, whereas the coal mining and washing sectors withdrawal approximately 14% of total water.

At the same time, indirect water savings from energy efficiency improvement are significant. As Fig. 6 shows, water withdrawal due to energy production also decreased by 15.9% (Ee-3%) and 22.6% (Ee-5%) in 2030 compared with the BAU scenario. Higher efficiency improvement can bring larger water saving benefits. Potential water savings are dominated by the reduction of coal production and electricity generation, reducing total water withdrawals by 3% and 21%. This co-benefit will also help governments to meet the water exploitation target set by the “3 Red Lines”. When energy efficiency is improved by 5% by 2030, water use for energy production can save 2.2% of total water use as set by “3 Red Lines” in China.

3.3. Sensitivity analysis

Key parameter values and model closures are decided subjectively which may bring uncertainty to the result of CGE model (Dai et al., 2011). Hence, a sensitivity analysis on the key parameter values was conducted to exam robustness of the model. Two main parameters were

Table 4
Scenarios for CGE model simulation.

Scenarios	Explanation
BAU (Business as usual)	This case assumes that current policies will remain unchanged and the Autonomous Energy Efficiency Improvement (AEEI) will increase 1% per year.
Energy efficiency scenario	Ee-3%: a 3% energy efficiency improvement in productive sectors at the energy composite level of the nested production structure. Ee-5%: a 5% energy efficiency improvement in productive sectors at the energy composite level of the nested production structure.

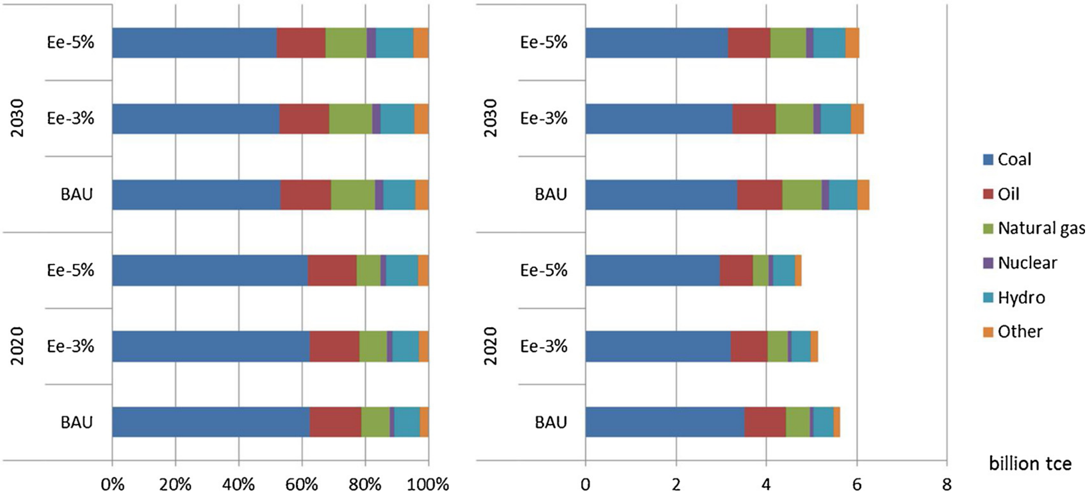

Fig. 3. The impact of energy efficiency improvement on China's energy sector.

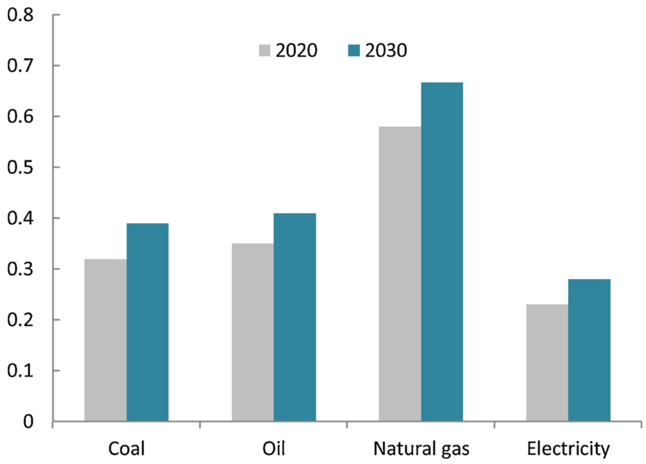

Fig. 4. Rebound rate for various energy types.

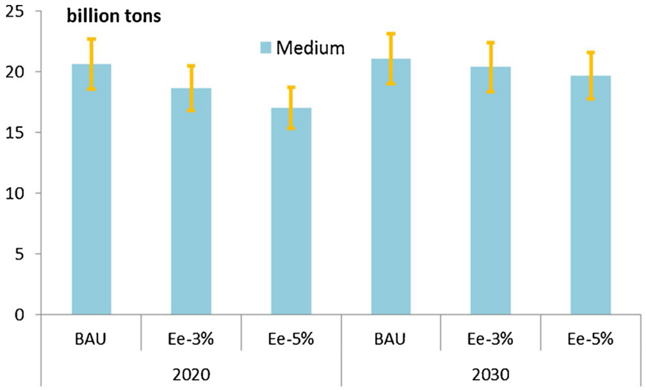

Fig. 5. China's CO_2 emissions in each scenario (billion tons).

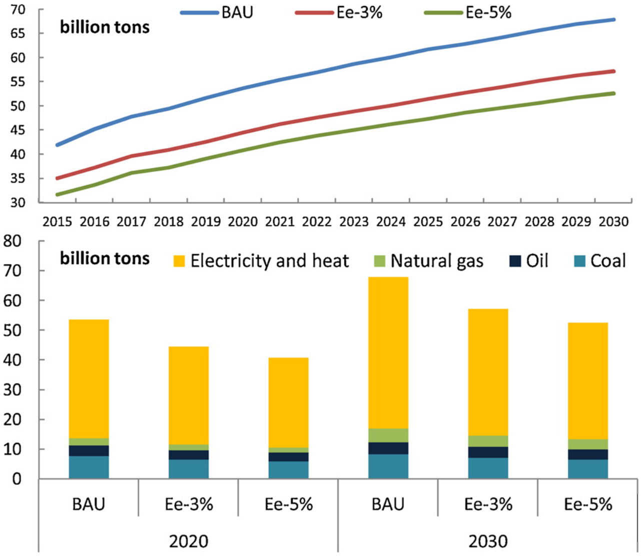

Fig. 6. Water withdrawal for energy production for China (billion tons).

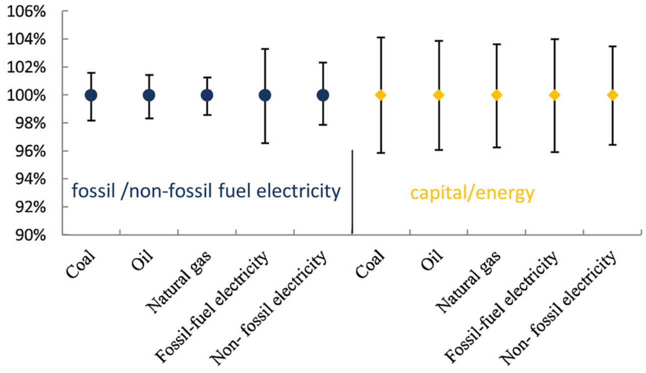

Fig. 7. Sensitivity analysis of key parameters.

tested, elasticity of substitution between fossil and non-fossil fuel electricity as well as the elasticity of substitution between capital and energy. The parameters were tested with a 10% increase and decrease from the base value to observe the influence on energy production under the BAU scenario (see Fig. 7).

Substitution between capital and energy shows a bigger influence on energy production compared with substitution between fossil and non-fossil fuel electricity. A drop of 10% from its base value will cause coal production to decline 4.1% and oil production to decline 3.8%. The elasticity of substitution among fossil fuels can influence final demand, and a higher elasticity of substitution allows greater flexibility for energy consumers to choose fossil fuels. It can have a greater influence on fossil fuel electricity, where a drop of 10% from its base value will cause fossil fuel electricity to reduce 3.4%.

4. Discussion and conclusions

4.1. Main findings with respect to the energy efficiency improvement

Water-energy interdependence is increasing, so the assessment and quantification of the co-benefit of sectoral policies is important for decision makers in China. Our work is able to show that in addition to conventional impacts, such as air pollution health impacts, energy policy will further affect water resources. Based on a dynamic CGE model, this paper estimated the impact of energy efficiency improvement on air pollution and water resources in China between 2015 and 2030. The results of our scenario analysis, demonstrated at the national scale, show that there are large co-benefits from improving energy efficiency in addition to air pollution reduction; water resources can also be saved. This finding means that the water system will benefit from a long-term energy development strategy due to the increasing interdependence between water and energy.

It is notable that energy production in China is placing more pressure on water resources. The energy production industry in China is still in the rapidly expanding stage, especially for thermal power. What's the worse, 47.3% of the thermal capacity is located in areas where water stress exceeds 40%, including Shandong, Henan, Shanxi and 22 other provinces (Green Peace, 2017). Total water use targets set by the "Strictest Water Resources Management System" (symbolically dubbed "3 Red Lines") (Ministry of Water Resources of the People's Republic of China, 2012) are important indicators that the government has been assessing every year; our results show that energy improvements can make a significant contribution to the realization of the water management goals. The co-benefit of energy management measures achieved by the water-energy nexus can help to mitigate future increases in energy demand and help ensure long-term water sustainability in China, especially for those regions with higher water stress.

4.2. Options for reducing water demand for energy production

These findings on indirect water saving also inform the government that, in addition to cooling technology retrofitting, improved energy efficiency can also relieve water pressure. Water supply is particularly important to thermoelectric power plants and poses additional pressure on local water resources. According to the "China Water Resources Bulletin 2015", water use by once-through cooling thermal power accounted for 36% of total industrial water use (Ministry of Water Resources of the People's Republic of China, 2017). A shift in cooling technology is considered to be helpful for water saving during energy production (Zhang et al., 2016a; Zhang et al., 2016b). Hence, regulators have proposed implementation of a cooling technology retrofit in some regions to save water. The results of this study show that improved energy efficiency can achieve thermoelectric cooling water savings comparable to other water saving methods. Further, cooling technology retrofits need large investments (Bartos and Chester, 2014; Loew et al., 2016) and may not be cost-effective for either the plants or the governments. From this perspective, the co-benefits highlighted in this study may change the result of a direct cost-benefit evaluation for policy makers when they evaluate the investment of energy and water saving technologies. This information will help to make better decisions in the management between water and energy trade-offs.

4.3. Limitations and future work

Scenario setting in this study is very simple, and only energy efficiency improvement was considered. Other scenarios, such as emission trading and carbon tax, are very important scenarios for China's future energy demand projections and also have a big impact on water resources. This analysis sets the same improvement rate for all energy sectors, without distinguishing different types of energy. We will improve this, and set up additional scenarios in future work in order to make the analyses more closely related to actual conditions. Furthermore, the current model is a national level model. Clearly, there are differences in energy production and water resource endowment amongst regions in China. Energy production will pose different water stress in different regions. Therefore, it would be necessary to develop a model at the regional level, to explore how efficiency improvements affect energy use and production in that region and evaluate related impact on regional water resources.

Last but not least, the technological cost problem related to energy efficiency improvements and other energy policies is important but was not taken into account in our model. Due to the lack of detailed technological information in the CGE model, it is hard to incorporate these costs in our recent model. The bottom-up models focus on sectoral and technological details are therefore well suited to the analysis of specific changes of technology (Böhringer, 1998; Cai et al., 2015; Fujimori et al., 2014, IPCC, 2001). Hence, in our future work, we will try to incorporate the cost of energy efficiency technology adoption by combining the CGE model with a bottom–up technology model such as MARKAL or LEAP.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.01.019.

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