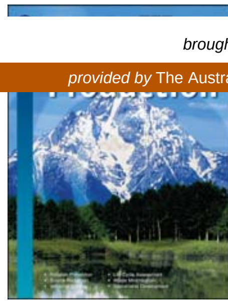


An analysis of the costs of energy saving and CO_2 mitigation in rural households in China

Weishi Zhang, David Stern, Xianbing Liu, Wenjia Cai, Can Wang

PII: S0959-6526(17)31618-9

DOI: 10.1016/j.jclepro.2017.07.172

Reference: JCLP 10175

To appear in: *Journal of Cleaner Production*

Received Date: 7 December 2016

Revised Date: 10 July 2017

Accepted Date: 21 July 2017

Please cite this article as: Zhang W, Stern D, Liu X, Cai W, Wang C, An analysis of the costs of energy saving and CO_2 mitigation in rural households in China, *Journal of Cleaner Production* (2017), doi: 10.1016/j.jclepro.2017.07.172.

An Analysis of the Costs of Energy Saving and CO_2 Mitigation in Rural Households in China

Weishi Zhang [a,*], David Stern [b], Xianbing Liu [c,*], Wenjia Cai [d], Can Wang [d]

[a] Department of Geography and Resource Management & Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong, China
[b] Crawford School of Public Policy, The Australian National University, Australia
[c] Institute for Global Environmental Strategies (IGES), Japan
[d] School of Environment, Tsinghua University, China

[Abstract] Households may imperfectly implement energy saving measures. This study identifies two factors resulting in imperfect use of energy-saving technology by households. Households often continue to use old technologies alongside new ones, and the energy-saving technologies have shorter actual lifetimes than their designed lifetimes. These two factors are considered when computing marginal energy conservation cost and marginal CO_2 abatement cost using data collected from a survey of rural households in three provinces in China. The results show that there are cost reduction for most space heating technologies, and their marginal abatement cost under full implementation ranges from -60 to 15 USD/t-CO_2, while the marginal abatement cost of cooking technologies ranges from 12 to 85 USD/t-CO_2. The marginal abatement costs of the majority of technologies increased after accounting for the two implementation factors. The marginal abatement cost in the imperfect implementation scenario is higher, with a range of -1 to 15 USD/t-CO_2 for space heating, and 18 to 165 USD/t-CO_2 for cooking. Assuming implementation factors are constant until 2035, annually achievable CO_2 abatement by 2035 is estimated to be 57, 11, and 10 Mt-CO_2/y in Hebei, Guizhou, and Guangxi Provinces.

Key words: Energy saving technology, cost estimation, rural households, China

[*] Corresponding Author: Xianbing Liu
Postal Address: Institute for Global Environmental Strategies (IGES),
2108-11, Kamiyamaguchi, Hayama, Kanagawa,
240-0115, Japan
Tel: +81-46-855-3700; Fax: +81-46-855-3709
E-mail Address: liu@iges.or.jp (Xianbing Liu); zhangweishi@link.cuhk.edu.hk (Weishi Zhang)

Abbreviations

GHGs	Greenhouse gases
MACC	Marginal abatement cost curve
MECC	Marginal energy conservation cost curve

Nomenclature

AE	**Adoption efficiency rate, %**
B	Maximum methane producing capacity for manure produced by swine, m^3 CH_4 per kg of VS excreted
COE	Annualized energy conservation cost of 1 GJ [USD/GJ]
COA	Annualized abatement cost of 1 unit CO_2 equivalent [USD/tCO_{2e}]
CRF	Annuity cost factor
c	Specific heat of water, 4.20 kJ/(kg°C)
d	Annual working days of biogas digester
DS	CH_4 density (0.00067 t/m^3 at room temperature (20ºC) and 1 atm pressure)
⊿EC	Energy conservation per household at the technologically maximum potential [MJ/y]
EF	Emission factor [gCO_2/kg fuel]
FC	Fuel consumption [MJ]
Hv	Latent heat of vaporization at atmospheric pressure, 2,257.2 kJ/kg
MCF	Lagoon methane conversion factor calculated by IPCC
MS	Fraction of manure handled in system annually [%]
RP	Household scale, people per household
RE	Removal efficiency [%]
Temp1	Original water temperature before heated, assumed to be the local temperature [℃]
Temp2	Water temperature after heated, data from the field survey [℃]
t	Lifetime of technology
h	The net calorific value of biogas, about 20,935 kJ/m^3
VS_{site}	Onsite daily volatile solid excreted for swine [kg]
W_{site}	Average animal weight of a defined livestock population at the project site [kg]
$W_{default}$	Average weight defaulted by IPCC in calculation [kg]
n	Abatement technology
hh	Household
i	Province

ref	Reference technology

Greek letters

$\boldsymbol{v}$	**Daily biogas generation** rate [%]
$\boldsymbol{\eta}$	Thermal efficiency of biogas cooker [%]
$\boldsymbol{\alpha}$	Shape parameter of Weibull distribution
$\boldsymbol{\lambda}$	Scale parameter of Weibull distribution

Highlights:

- This paper estimates energy use and CO_2 abatement costs of rural residents in China.
- Technologies have shorter lifespans in the field than their designed lifetimes.
- A rural household survey was carried out in Hebei, Guizhou, and Guangxi Provinces.
- Marginal abatement cost of most technologies increased after accounting for the adoption efficiency and lifetime.

1. Introduction

Energy consumption is one of the most fundamental drivers of climate change globally. The residential sector accounts for approximately 35% of total energy consumption on average in developing countries, while this number is around 20% in developed economies (Nie and Kemp, 2014). In China, residential energy consumption consists of roughly 10% (Yuan et al., 2015) to 11% of the country's total (Nie and Kemp, 2014). In rural China, non-commercial technologies and biomass fuels are widely used. Biomass accounts for about 40% of total residential energy use, followed by coal with a share of 19%. The large share of non-commercial fuels increases the difficulty of estimating energy consumption and costs in rural areas in China (Xiao et al., 2014). Various policies and subsidies have been launched in China since the 1990s with the primary purpose of accomplishing energy savings or improving the living condition of residents at minimum cost.

In practice, households and enterprises are hindered from approaching the optimal level of energy efficiency due to various market barriers (Hirst and Brown, 1990), which is referred to as the 'energy efficiency gap' (Schipper et al., 1989). Energy efficiency technologies that are financially cost-effective might not be as widely adopted by potential users as expected. The actual technology diffusion rates will be lower than the optimal rates (Jaffe and Stavins, 1994). In this paper, the effect of imperfect technology adoption and implementation on carbon emissions abatement and abatement costs in rural Chinese households are investigated.

Marginal abatement cost curves (MACCs) are a tool for comparing different abatement measures (Huang et al., 2016). A MACC shows the relationship between reduction in emissions and the marginal cost per unit of abatement. MACCs can be seen as abatement supply curves, which show the optimal order of options to meet an abatement target. The abatement achieved by the options is relative to a reference technology. MACCs should also take into account the implementation factors of the various technologies.

MACCs can be generated using an expert-based or model-based approach. The former are referred to as bottom-up MACCs (Meier, 1982) and have the advantage of the full use of technology information. This approach has been criticized because it does not take into account the institutional and behavioral context (Vogt-Schilb and Hallegatte, 2011) and does not reflect implementation barriers (Kesicki and Ekins, 2012). Model-based top-down MACC models are derived using Computable General Equilibrium (CGE) models, input-output (IO) models, or other simulation models (Ellerman and Decaux, 1998). Model-based MACCs have the advantage of taking into account the interactions among abatement measures. On the other hand, models introduce many assumptions, which are not necessarily realistic. An integrated MACC may be built by combining bottom-up and top-down approaches. For example, the Regional Air Pollution Information and Simulation (RAINS) model was developed to explore emission mitigation pathways of major air pollutants and greenhouse gases (Amann et al., 2004).

MACCs have rarely been used to analyze the residential sector, especially for rural households in China. Energy consumption patterns are quite different in rural and urban areas as non-commercial energy is widely used in rural areas (Xiao et al., 2014). Rural buildings are estimated to account for 33% of the CO_2 abatement potential in the entire building sector in China (Xiao et al., 2014). Researchers usually focus on urban residential (Mortimer et al., 1998); or commercial buildings (Hong et al., 2017), although their abatement potential is much less than rural residential buildings. Examples of research on carbon emissions from the residential sector include: Zhang et al. (2015) who calculate China's carbon emissions from urban and rural households in the period 1992-2007; Zhang and Zhou (2016) who investigate the carbon abatement effects of policy regulations and Yuan et al. (2017) who look at the effects of building standards in the residential sector.

Previous research on the residential sector in China suffers from four main weaknesses.

First, previous research does not distinguish the rural residential sub-sector from the urban sector and the, marginal abatement cost (MAC) and abatement potential of different technologies in the rural residential sector have not been compared.

Second, the influence of implementation factors and household behavior on technology adoption and abatement are rarely quantified. Previous studies failed to consider the gap between households' actual behaviors and an idealized scenario of full adoption. Implementation gaps increase abatement cost compared to the full implementation scenario. Researchers found it hard or even impossible to quantitatively include these implementation factors into their analysis (Streets et al., 2001). They simply assume an implementation rate (Rubin et al., 1992), due to data availability and method constraints.

Third, most existing studies assume full implementation without clarification (McKinsey & Company, 2009b), and the uncertainty behind this assumption has rarely been discussed.

Regional differences are seldom distinguished. Variations in MACCs at the provincial level in China have rarely been considered (Du et al., 2015). Provinces in the north and south of China greatly vary in technology feasibility and energy consumption patterns, due to the climate, local resources, and governance differences.

Addressing these weaknesses in previous research, this study investigates rural households in three selected provinces in China and gives insights for improving existing approaches of constructing marginal energy conservation cost curves (MECC) and MACC. The influences of implementation factors on abatement volume and abatement cost are quantified accordingly. The regional differences are also discussed in this paper.

This paper is structured as follows: Following the Introduction, the research method is given in

Section 2. Section 3 describes the data collection survey. Marginal cost curves for energy conservation and greenhouse gas (GHG) abatement are presented in Section 4. A sensitivity analysis is carried out and weaknesses are discussed in Section 5. Section 6 gives the conclusions.

2. Research method

2.1 Analysis framework and scenarios

MECC and MACC are useful tools for ranking technology options from lowest marginal cost to highest. The analysis framework is shown in Fig.1. Ten technology options are identified in the field survey for three types of end services. Among these, five cooking abatement technologies are identified: improved brick stove, cement household biogas, steel-glass biogas, improved metal stove, and centralized biogas. Four technologies serve for space heating. They are: individually improved space heating stove, household biomass gasifier stove, biomass briquette stove, and elevated huokang – a heated bed platform. Solar water heaters serve as a abatement technology for water heating.

The reference technology refers to the traditional technology, which is replaced by abatement technologies. When studying energy saving and emission reduction potentials of interventions in rural households' energy consumption, previous researchers use 'coal consumption or solid biomass fuels substitution' as the reference technology (Aunan et al., 2013). In our study, the reference technology for cooking is a traditional brick stove burning straw and wood. There are two reference technologies for space heating. Where coal is used, the reference technology is a traditional metal coal stove, where straw and wood are used is a grounded Huokang. The reference technology for water heating is an electric water heater.

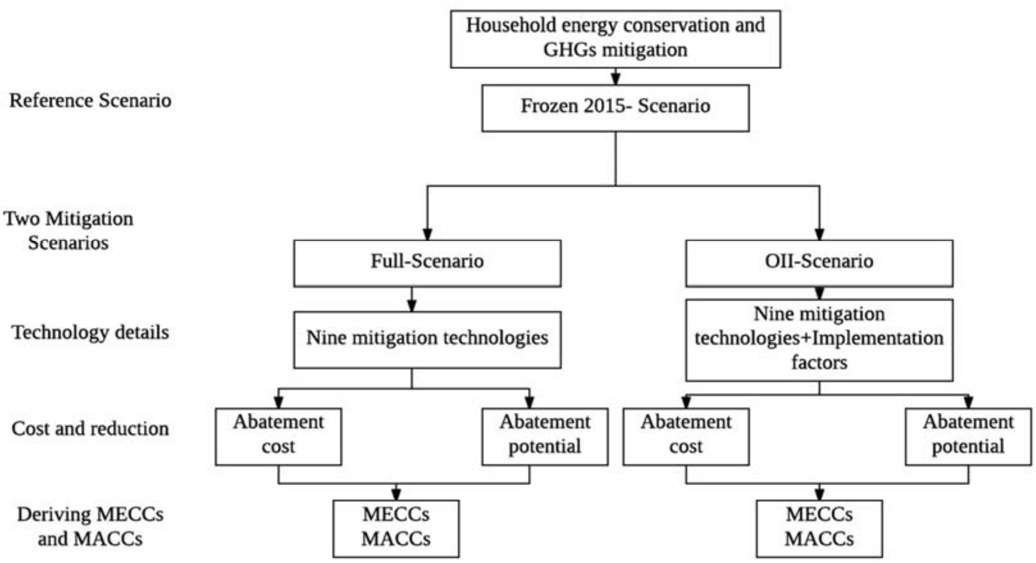


Fig.1. Analysis framework of this study.

The abatement cost and abatement potential for each technology option as the incremental cost of the abatement technology replacing the reference technology are calculated. Unit energy conservation cost (*COE*) is defined as the cost of saving 1 GJ of energy. Unit CO_2 abatement cost (*COA*) is defined as the abatement cost of 1 kg of CO_2 equivalent. Capital investment, operational and maintenance cost, and fuel cost are covered in the cost analysis. Energy conservation and CO_2 abatement potential in different scenarios are estimated. Energy demands of rural households through 2035 are projected based on energy consumption in 2015 obtained from the field study. To construct MECCs and MACCs, the cost effectiveness of each advanced technology is compared and ranked with respect to its marginal cost from the lowest to highest. Technologies with lower removal efficiency and higher unit reduction cost are excluded from further analysis.

The energy efficiency technologies can only be adopted by households who are not using these devices. The maximum energy conservation potential is estimated by taking this into account. Capital investments in existing technologies are treated as sunk costs, and so only fuel costs and maintenance costs are considered for the baseline technologies.

Three scenarios are used this research (Table 1). Frozen 2015-Scenario assumes that the observed energy consumption level in 2015 remains constant to 2035. OII-Scenario is the Observed Imperfect-Implementation Scenario, which is the scenario considering the implementation factors (the most likely achievable MECC and MACC under imperfect implementation). Full-Scenario is the calculated Full-Implementation Scenario, which does not consider the two implementation factors. The difference in MACCs between Full-Scenario and OII-Scenario is a function of the two implementation factors identified by authors from the field survey. One factor is due to the shorter lifetime *t* of advanced technologies in the field compared to their designed lifetime, which will induce much higher annualized costs. Households stopped using some of the energy-saving technologies before the designed lifetime because of the following reasons: 1) lacking of energy resources, for example, biogas; 2) some technologies requires skilled labor for operation and maintenance (O&M); or, 3) habits (households preferred the traditional stoves). The other factor is due to the lower adoption efficiency (*AE)*, which is the annual serving days of a technology divided by 365. In OII-Scenario, *AE* is lower than 100% for most options. In Full-Scenario, *AE* ideally equals to 100%.

Table 1

Descriptions and two implementation factors defined in three scenarios.

Scenario	Descriptions	Lifetime of device (*t*)	Adoption efficiency (*AE*)
Frozen 2015-Scenario	Shares of current technologies among rural households keep	Predicted median lifetime of abatement technology	Observed *AE* in field survey

	constant to 2035		
Full-Scenario	Abatement technologies at maximum adoption, gradually from the lowest MAC to the highest	Designed lifetime of abatement technology	100%
OII-Scenario	Imperfect implementation factors on Full-Scenario	Predicted median lifetime of abatement technology	Observed *AE* in field survey

Fig. 2 illustrates the relationship among the three scenarios. The x-axis is the time horizon; the y-axis shows the energy consumption level. The projected reduction gap between the Full-Scenario and the OII-Scenario is positive and is shown as the distance between the two lines AC-AB, equal to the length of BC. The cumulative reduction gap is the area between the two lines, shown as the area of BOC.

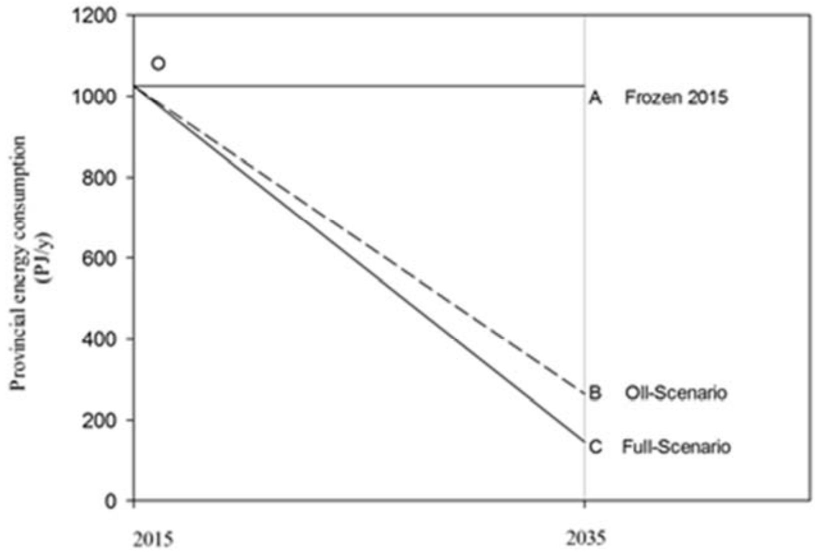


Fig.2. Illustration of the three scenarios defined in this study.

2.2 Calculations of marginal energy conservation cost and marginal abatement cost

The cost per unit energy saving offered by energy conservation technology *n* in household *hh* in region *i* is denoted by COE and can be calculated by the levelized cost of energy technology compared with no control option, and divided by the annual energy conservation, as in Eq. (1).

$$COE_{n,hh,i} = \frac{NPV_{n,hh,i} \cdot CRF_n}{AE_{n,hh,i} \cdot \Delta EC_{n,hh,i}} \quad (1)$$

where $NPV_{n,hh,i}$ is the net present value of technology *n* in basic year 2015, made up of investment cost, maintenance, and operational cost, which were obtained from the field survey; $\Delta EC_{n,hh,i}$ is the energy conservation per household using technology *n* at the technological maximum potential.

The annuity cost factor CRF_n of technology *n* is a function of discount rate *r* and the lifetime, *t*, of the technology device (Lindeburg, 1992), as shown in Eq. (2).

$$CRF_n = \frac{(1+r)^t \cdot r}{(1+r)^t - 1} \quad (2)$$

Either private or social discount rates have been adopted in previous studies. McKinsey & Company (2009b) and Treasury (2003) used a social discount rate of 4%-5%. Mortimer et al. (1998), Ruderman et al. (1987), and Xiao et al. (2014) used a private discount rate, ranging from 12%-25%. The private discount rate in the residential sector, which reflects the perspectives of individual consumers, is naturally higher than the social discount rate. When there are government subsidies for equipment, households pay part of the fixed investment cost. The discount rate could be adjusted to be lower. In this study, 8% is adopted as a compromise value.

AE and *t* are two implementation factors that may cause a gap between energy saving in the Full-Scenario and OII-Scenario. The annual serving days of a technology by each household is collected from the field survey. *t* is the lifetime of the technology, in other words, the number of years the equipment is used by end users. In Full-Scenario, *t* is equal to the designed lifetime of the equipment. In OII-Scenario, *t* is obtained from the field survey carried out by the authors. There are two situations. One is that the use of device is observed to be no longer used. In this case, *t* equals to the observed in use year of equipment. Eq. (1) is then adopted to calculate COE.

In the other case, the households are still using the technology during the survey, and so it is impossible for the authors to follow all the households until the equipment is discarded. These data are, therefore, censored data. We assume that the lifetime of equipment fits a two parameter Weibull distribution, similar to the estimation method adopted by Cai et al. (2015). In year *t*, the cumulative survival rate is roughly estimated by Eq. (3).

$$S(t) = \exp\left[-\left(\frac{t_i}{\lambda}\right)^{\alpha}\right] \quad (3)$$

where, α and λ are the shape and scale parameters of the Weibull distribution to be estimated. The central lifetime of equipment can be obtained when the cumulative survival rate is equal to 0.5, as shown in Eq. (4).

$$\hat{t}_m = \left[\log 2 \cdot \hat{\alpha}\right]^{\frac{1}{\hat{\lambda}}} \quad (4)$$

The range of *t* is between the observed age and the designed lifetime for each censored sample.

Eq. (1) is calculated in these cases by simulating 2,000 realizations of *t* randomly. An average value of COE is calculated for each technology. According to the "law of large numbers", the sample mean approaches the theoretical mean when sample size increases. The calculated average COE can be used as the theoretical mean value of COE for all sample households. Matlab is used for programming of the calculation, and the code is provided in Supporting Information S6.

Adopting a similar approach to the RAINS model (Klimont et al., 2002), advanced technologies for the same energy demand type (cooking, space heating and water heating) are substituted from the least cost technology to the highest one with additional cost per unit of incremental energy conservation, and the MECC of technology *n* denoted by $MECC_n$ is calculated by Eq. (5):

$$MECC_{n,i} = \frac{\overline{COE}_n \cdot \Delta EC_n - \overline{COE}_{n-1} \cdot \Delta EC_{n-1}}{\Delta EC_n - \Delta EC_{n-1}} \quad (5)$$

where COE_n is the average unit energy conservation cost of observed samples. The energy conservation potential of each technology *n* is presented as a segment on the MECC curve.

COA_n is the average value of annualized abatement cost of GHG emissions abatement based on energy conservation in units of USD/t-CO_2. COA_n, can be calculated at the household level using Eq. (6).

$$COA_{n,hh,i} = \frac{NPV_{n,hh,i} \cdot CRF_n}{AE_{n,hh,i} \cdot \Delta EC_{n,hh,i} \cdot EF_{ref} \cdot RE_{n,hh,i}} \quad (6)$$

where EF_{ref} is the emission factor of reference technology. Removal efficiency *RE* of the technology *n* is defined as the share of CO_2 abatement by adopting advanced technology divided by emissions from the reference technology when meeting the same energy demands, as calculated by Eq. (7).

$$RE_n = \frac{EF_0 \cdot FC_0 - EF_n \cdot FC_n}{EF_0 \cdot FC_0} \quad (7)$$

EF_n denotes the emission factors of each abatement technology. EF_n used in this paper are listed in the Supporting Information Table S1. The efficiencies of different stove types are listed in Supporting Information Table S2.

The average unit CO_2 abatement cost, $\overline{COA_n}$, is calculated in a similar way to COE. The MAC of technology *n* can be calculated based on Eq. (8), which is similar to Rypdal et al. (2009) and Rubin et al. (1992). All technologies are ranked according to *RE* from the lowest to the highest, and technology options are replaced by *n+1* and so forth.

$$MAC_{n,i} = \frac{\overline{COA}_n \cdot RE_n \cdot AE_n - \overline{COA}_{n-1} \cdot RE_{n-1} \cdot AE_{n-1}}{AE_n \cdot RE_n - AE_{n-1} \cdot RE_{n-1}} \qquad (8)$$

MECC and MAC curves in Full-Scenario and OII-Scenario are constructed following the same steps as introduced above in this section. The difference is the input parameter of the two implementation factors.

2.3 Estimation of energy consumption by end-use services

Rural households have a complex energy consumption mixture, mainly because of the wide use of non-commercial energy, which also causes difficulty in cost estimation. The construction and maintenance costs of self-constructed equipment can be obtained from the field survey, by multiplying all the materials consumed by the local prices of materials and summing up. The results are shown in the Supporting Information Table S2. The methods adopted to calculate the energy consumption of household biogas digesters, large centralized biogas systems, and solar water heaters are described below.

2.3.1 Energy consumption of biogas generation

Heat generation by the small-scale household biogas digester is calculated by adopting the method from UNFCCC (2013), as shown in Eq. (9).

$$EC = v \cdot d \cdot h \cdot \eta \qquad (9)$$

where, *EC* denotes for heat generation by biogas; v is the daily biogas generation rate (m^3/d), which is estimated based on household number, averaged meals need daily, which were obtained from the field survey. The biogas needs for one meal per person is assumed to be 0.16 m^3, the same as adopted by Gosens et al. (2013); d is the annual working days of biogas digester, which was obtained from the field survey; h is the net calorific value of biogas, about 20,935 kJ/m^3; and, η is the thermal efficiency of the biogas cooker.

The summary of calculation data of the four large biogas systems is given in Table 2. Two 1,000 m^3, a 400 m^3 and a 90 m^3 systems were surveyed in this study.

Table 2

Summary of calculation data of large biogas projects.

	Hebei	**Guizhou**	**Guangxi**	
	Badaogou	Boxiangtai	Zengyutun	Laipa
Installed capacity (m^3)	1,000	1,000	400	90
Daily output (m^3/d)	650	200	123	40
Annual in use days (days)	365	60	90	240
Adoption efficiency (%)	100	16	25	66

Installation households	216	136	50	22

To verify the reported data, and as the input source of the centralized biogas project is dung only, the biogas output in this research is estimated according to the pig farm scale and based on the method provided by IPCC (2003). The emission factor for methane emission from manure management can be calculated by Eq. (10).

$$EF = VS_{Site} \cdot d \cdot B \cdot Ds \cdot MCF \cdot N \cdot MS \cdot 100 \tag{10}$$

where *d* is the working days of the biogas system annually, which is obtained from the field survey; *B* is the maximum methane producing capacity for manure produced by swine, m^3 CH_4 kg^{-1} of VS excreted; *MCF* is the lagoon methane conversion factor calculated by the IPCC; *MS* is the fraction of manure handled in the system annually; *N* is the annual number of swine; *Ds* is CH_4 density (0.00067 t/m^3 at room temperature (20ºC) and 1 atm pressure);

VS_{site} is the onsite daily volatile solid excreted by swine, adjusted by the average weight of pig provided by the farm owner that can be further estimated by Eq. (11).

$$VS_{site} = \left(\frac{W_{site}}{W_{default}} \right) \cdot VS_{default} \tag{11}$$

where $VS_{default}$ is the default daily volatile solid excreted by swine (kg dry matter per day per head); W_{site} is average animal weight of a defined livestock population at the project site; $W_{default}$ is the animal weight defaulted by IPCC. Parameters in Eq. (9)-(11) are shown in Supporting Information table S3.

2.3.2 Energy consumption of solar water heater

Adopting the method used by Niu et al. (2014), the total annual heat produced by solar water heater (EC_{solar}) can be calculated by Eq. (12).

$$EC_{solar} = RP \cdot d \cdot [w \cdot c \cdot (temp_2 - temp_1) + 0.1 \cdot w \cdot Hv] \tag{12}$$

where *RP* is household scale based on data from the field survey. *d* is annual use days of solar water heater, data from the field survey. *w* is daily consumption water amount, which is calculated based on data of residential water use in 2014. The number in China Statistics Yearbook is 47.6 kg/d (NBSC, 2015), and residential building hot water consumption of solar water heater ranges between 40-80 L/d/person in national standard of solar water heater in buildings (MOHURD, 2003). In underdeveloped areas, hot water consumption is estimated to be 26.2 L/d/person by a survey study carried out by Du (2011). The rough data of households on their daily hot water consumption was obtained, including washing, bathing and put an adjustment coefficient of 0.7 on the national standard, which is 28 kg/d/person. *c* is the specific heat of water, 4.20 kJ/(kg°C); *Hv* is the latent heat of vaporization at atmospheric pressure, 2,257.2 kJ/kg; *Temp1* is the original water temperature before being heated, which is assumed to be the local temperature; *and Temp2* is the water temperature after being heated, based on data from the field survey.

3. Data used in this study

Three provinces and regions in different climate regions in China were chosen in this study, as shown in Fig.3. Households in a total of 22 villages of seven municipal cities were interviewed during June to August 2015 by a group of interviewers. The black dots show the approximate locations of the cities. From north to south, Hebei province is located in the North China Plain with 'Hot summer - Cold winter' climate, in which 236 valid household samples were interviewed. Guizhou is located in the south-western Guizhou plateau, which has 'Cool summer - Mild winter', and 320 households were interviewed there. Guangxi province is based in south China Guangxi basin, which has a climate of 'Hot summer - Warm winter', where 112 households were interviewed.

Fig.3. Field survey sites in three provinces.

The questionnaire is structured as follows. First, household membership and income information are collected. Second, both commercial and non-commercial fuels were recorded. Three end-use services are distinguished, which are cooking, water heating and space heating. The technologies adopted by the household were also recorded. Third, initial costs, operation and maintenance costs, and fuel costs are included in the questionnaire. We requested specific information for determining the implementation factors: the frequency of adoption annually (AE) and the lifetime (t) of the equipment.

Ten energy-saving technologies in three end-services are observed in the field survey, which are identified for the current year until 2035. The current ownership of each advanced technology is summarized in **Table 3**, which is used for calculating energy consumption and emission level in Frozen 2015-Scenario. Installed ownership indicates households who installed the technology. The observed ownership for 2015 indicates the ownership that was been observed in field survey in 2015, meaning that households are still using the technology at the time of the survey. It presents the performances of the technologies and the Frozen 2015-Scenario is calculated based on this data. CO_2 emission factors of each technology and fuel type are obtained from various previous studies, and the median value is used in this research, as given in the Supporting Information S2.

Table 3

Ownership of energy-saving technologies in three regions in 2015 (sets/100 households).

End-use service	**Energy-saving technology**	**Hebei**		**Guizhou**		**Guangxi**	
		Installed	2015	Installed	2015	Installed	2015
Cooking	Improved brick stove	24	4	0	0		
	Household biogas	25	3	39	19	34	11
	Steel-glass biogas			7	0		
	Improved energy-saving stove			13	4	13	
	Centralized biogas	1	1	1	1	1	1
Space heating	Improved metal stove			12	4		
	Household gasifier			14	1		
	Biomass briquette stove	9	0	0	0		
	Elevated Huokang	23	23	0	0		
Water heating	Solar water heater	47	47	48	48	29	29

Data on current centralized biogas users from previous studies and government reports are adopted to estimate the current generation of centralized biogas projects, as shown in **Table 4**.

Table 4

Estimation of current users of centralized biogas systems in the three regions.

	Current reported mid-large scale systems	**Reported total annual generation**	**Approximate regional total households using centralized biogas**	**Reference**
Hebei	1,453	17,430,000 m^3 (by 2012)	26,250*	(HBG, 2013)

Guizhou	639	11,508*	(Chen, 2011)
Guangxi	1,000 (by 2012)	18,066*	(GXG, 2009)

* For mid and large centralized biogas systems, annual biogas needs per household is approximately 664 m^3/y, calculated by field survey data.

The projection method of the energy demands of rural households from 2015 to 2035 is introduced below. Regional energy consumption and CO_2 emission level are scaled up based on the ratio of the number of sampled households and the total rural household number reported in the National Statistical Yearbook in the three provinces, which were 11.7, 6.8, and 7.9 M households in 2014 (NBSC, 2015). The net annual population growth rate was approximately 0.5 % in the past 10 years (NBSC, 2015). The annual urban population growth rate averaged 1.3 % (2003-2014), and the average number of people per household is 2.9. The net annual growth rate of rural household numbers is estimated to be about -0.3 % when projecting to 2035. The annual growth rate of real rural household income was 9 % from 2004 to 2014, and the energy consumption elasticity coefficient was reported to be 0.3 in 2014 (NBSC, 2015). The energy consumption growth rate is approximately to be 2.7 %. In common with most of the existing literature discussing short and mid-term strategies (McKinsey & Company, 2009a; 2009b), constant energy prices are assumed in this paper. There are two reasons for this assumption. One is that in the rural residential sector, the energy price is under great uncertainty. The other reason is that non-commercial energy fuels take larger shares, and the variation of energy price will have less influence on the results. Since this study aims at modeling the abatement gaps caused by implementation factors, a consistent assumption among all regions will not cause significant difference in the conclusion.

4. Results

4.1 Energy consumption and GHG emissions of the households

Fig.4 and Fig.5 show energy consumption per household and CO_2 emission level per household in 2015. It is a description of the field survey results. The two figures illustrate the energy consumption level and CO_2 emission level in 2015.

Fig.4 illustrates the energy saving achieved by replacing the reference technologies by abatement technologies, and actual observed energy consumption, which is then used in the Frozen 2015-Scenario. Energy consumption is slightly different in the three regions for cooking, and almost the same for water heating. There are no space heating demands in Guangxi, while energy consumption of space heating in Guizhou is less than that of Hebei due to the difference in local climate and temperature.

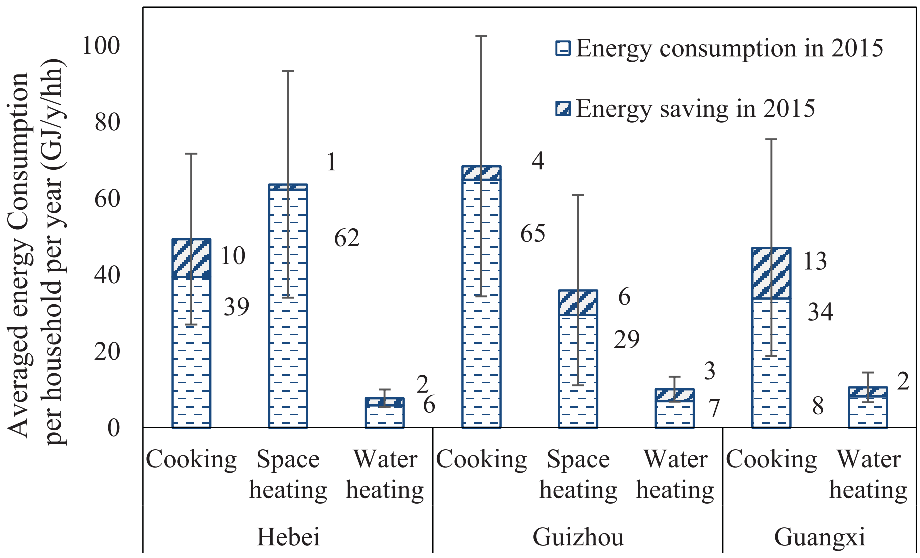


Fig.4. Energy consumption and energy-saving from existing technologies per household in 2015 by cooking, space heating and water heating in Hebei, Guizhou and Guangxi (±Standard Deviation (S.D.)).

The annual CO_2 emission level per household and annual CO_2 abatement by 2015 are illustrated in Fig.5. At the household level, Hebei has higher CO_2 emissions due to space heating, and in 2015, the average annual household emission for space heating there was about 6,293±2,400 kg-CO_2. This number is much lower in Guizhou -3,155±1,008 kg-CO_2. Emissions from cooking are the highest in Guangxi in 2015, followed by Hebei and Guizhou.

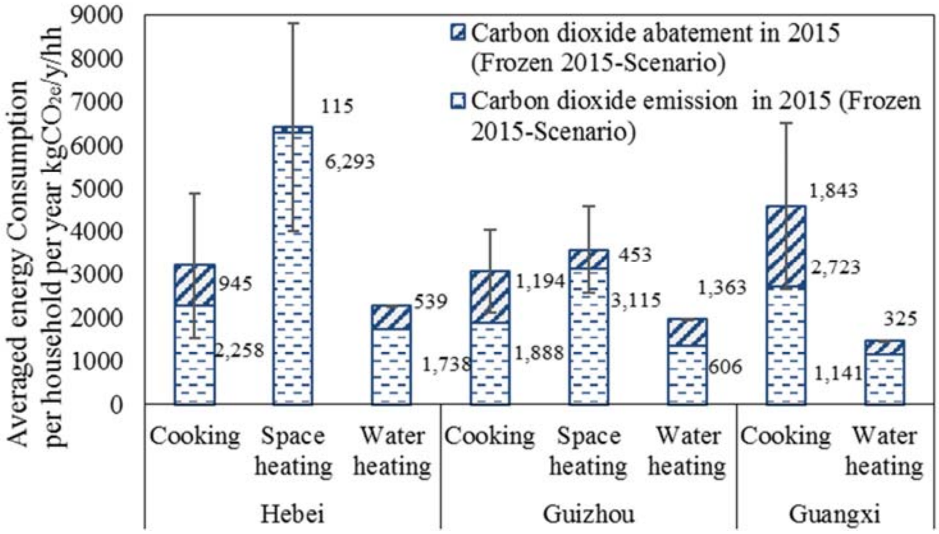


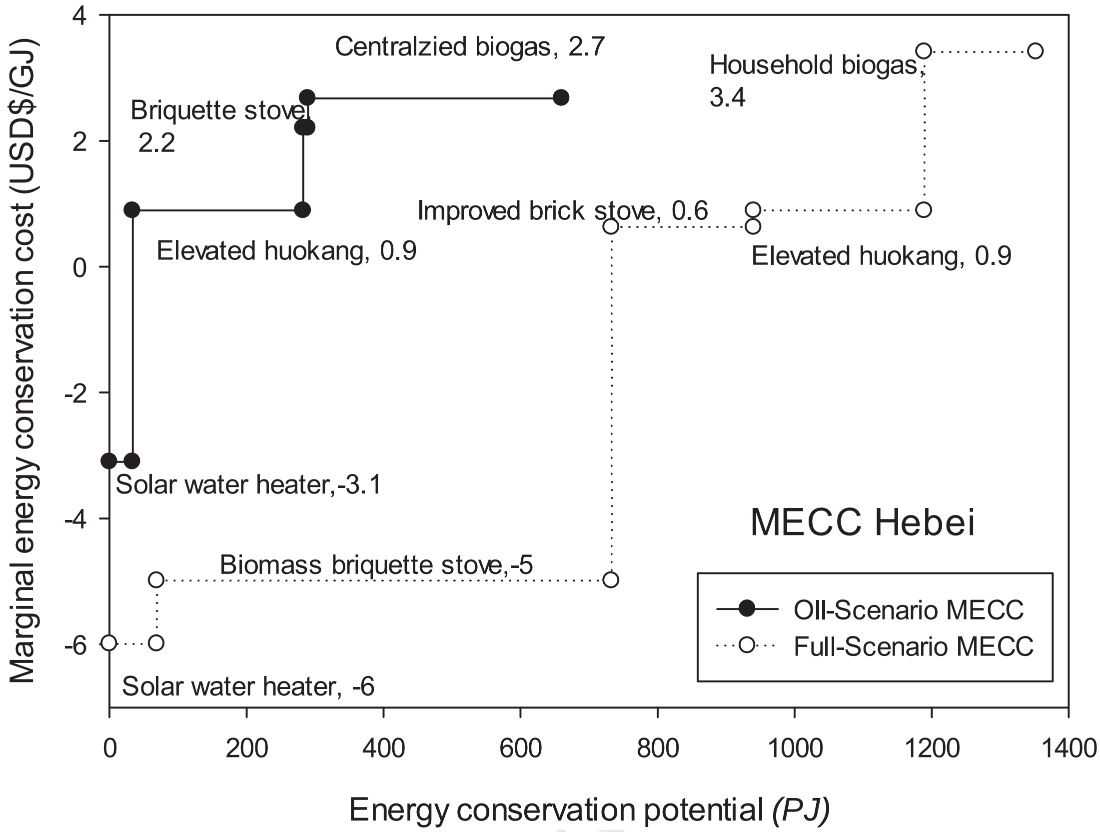
Fig. 5. CO_2 emission and CO_2 abatement abatementper household from existing technologies in 2015 by cooking, space heating and water heating in Hebei, Guizhou, and Guangxi (± Standard

Deviation (S.D.)).

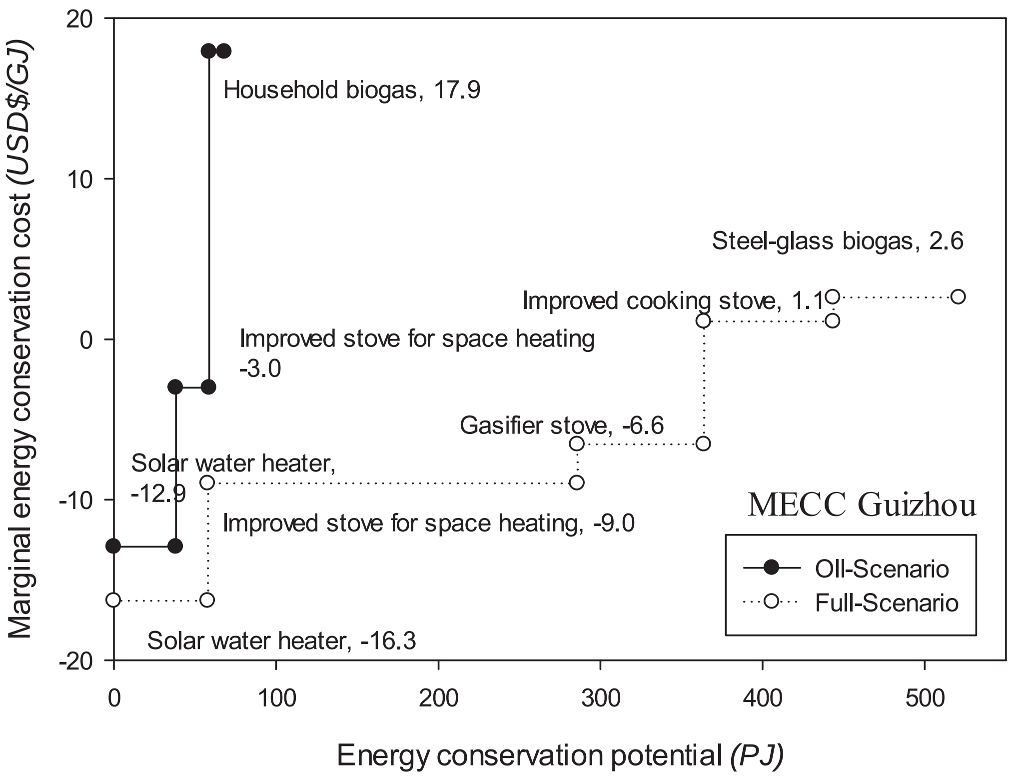
4.2 Marginal energy conservation cost curve (MECC)

For each of the ten technology options defined in Section 2.1, both energy saving cost and energy saving potential are calculated. Technologies are ranked in ascending order by marginal energy saving cost to construct the MECC. Fig.6 (a)-(c) illustrate the MECC for Full-Scenario (solid line) and OII-Scenario (dot line) in the three provinces. In Full-Scenario, the cost of reduction technologies ranges between -16.3 and 29.3 USD/GJ. In Hebei, solar water heater, biomass briquette stove, improved brick stove, elevated huokang, and household biogas are selected and ranked from the lowest cost to the highest. In Guizhou, solar water heater, improved energy saving stove, gasifier stove, improved cooking stove, and steel-glass biogas are selected. In Guangxi, solar water heater, improved cooking stove and household biogas are selected. In OII-Scenario, when considering the two implementation factors, the rankings of abatement technologies and MECC were changed. The technology energy saving cost based on the MECC in OII-Scenario ranges between -14.1 to 17.9 USD/GJ.

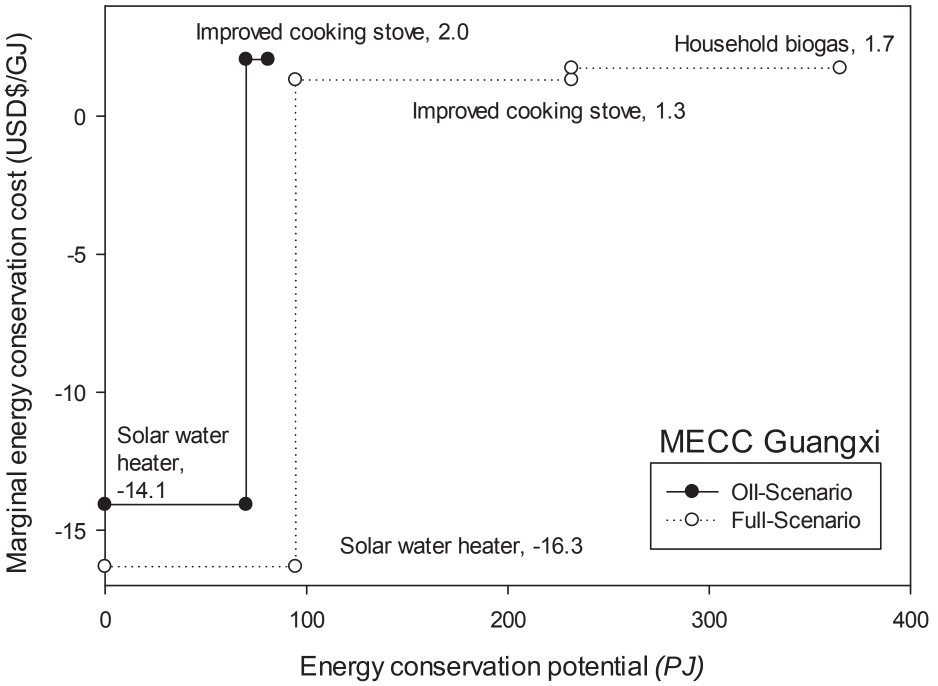
The scale of the MECC shows the maximum energy conservation potential that could be achieved in Full-Scenario and OII-Scenario accordingly. In Full-Scenario, the maximum annual energy conservation potential that could be achieved by technology options is 1,361, 524, and 368 PJ in Hebei, Guizhou and Guangxi. In OII-Scenario, the maximum annual energy conservation potential in the three regions is 665, 72 and 81 PJ. The gap of annual energy conservation between Full-Scenario and OII-Scenario is 697, 452 and 286 PJ.

410 

411 (a) MECC Hebei

412 

(b) MECC Guizhou



(c) MECC Guangxi

Fig. 6. (a)-(c). MECC in the three provinces, (a) Hebei, (b) Guizhou, and (c) Guangxi at the regional scale (Exchange rate between CNY and USD is 1 CNY = 0.154 USD, and real discount rate = 8 %).

4.3 Marginal abatement cost curves (MACC) of GHG emissions

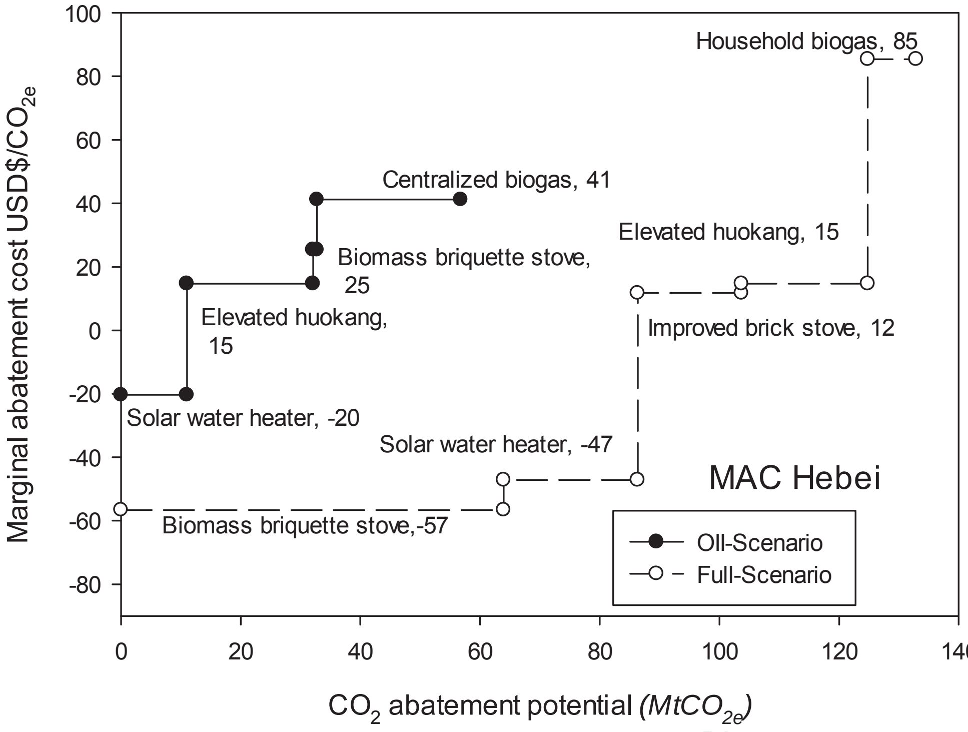
Fig. 7 (a)-(c) compares the MACC with and without the two implementation factors in the three regions individually. Compared with the results in Section 4.2, the MACC and MECC are highly consistent. The reason is that CO_2 abatement in this study only covers energy consumption related emissions, and non-energy-related options are not included.

The difference between the two MACC curves in Full-Scenario and OII-Scenario implies that, when considering the two implementation factors, the abatement technologies are re-ranked on the MACCs. The marginal cost of abatement technologies increases when considering implementation factors. In Full-Scenario for Hebei, five technologies selected from the lowest MAC to the highest are: solar water heater, biomass briquette stove, improved brick stove, elevated huokang and household biogas. Four abatement technologies are selected when considering the two implementation factors. They are solar water heater, elevated huokang, biomass briquette stove, and centralized biogas.

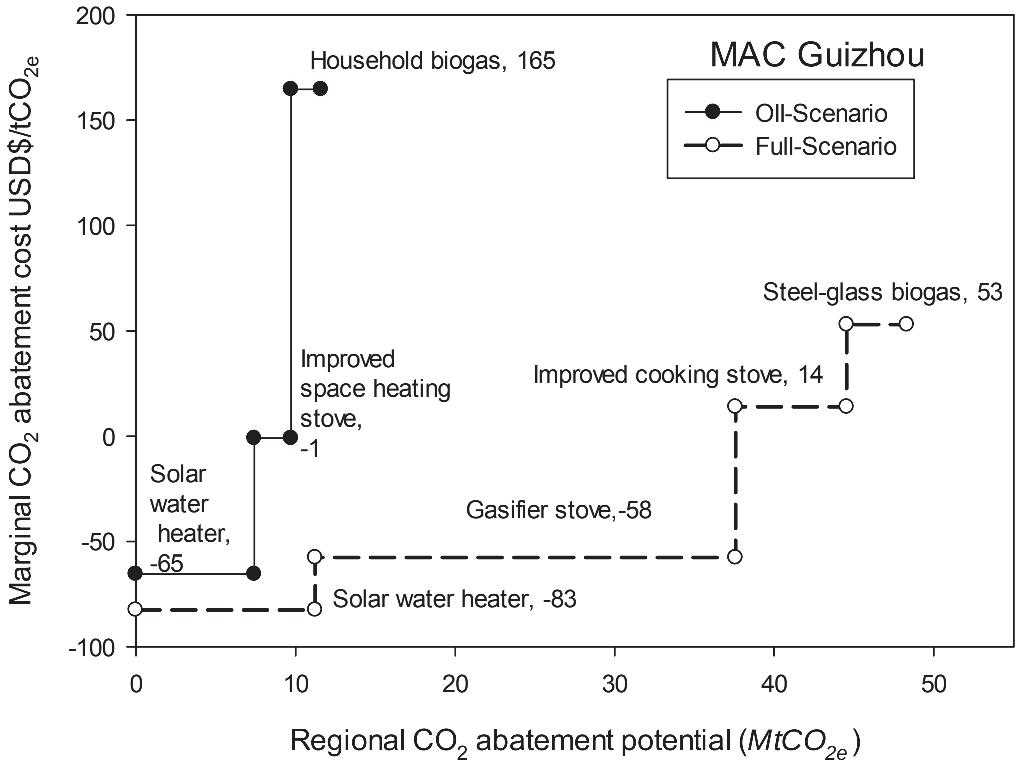
The y-axis of the MACC shows the MAC of each technology option. Taking into account the implementation factors also increased the MAC of the majority of technology options. In Full-Scenario, the MAC of technology options ranges from -117 to 85 USD/t-CO_2. In OII-Scenario, MAC ranges from -101 to 65 USD/t-CO_2. More specifically, in OII-Scenario, solar water heater is the most cost-effective technology in all three regions. Its MAC is calculated to be negative, with a number of -101 USD/t-CO_2 in Guangxi, and -65 and -201 USD/t-CO_2 in Guizhou and Hebei. In Full-Scenario, MAC of solar water heater ranges from -117 to -47 USD/t-CO_2. Previous research finds that the cost effectiveness of centralized biogas is lower than household biogas digesters (Rehl and Müller, 2013). In Hebei, the MAC of household biogas is positive at 85 USD/t-CO_2, while centralized biogas has been deducted in the Full-S scenario. In Guizhou, steel-glass biogas is more cost-effective than the traditional type or the centralized biogas system, and the MAC of this technology is 53 USD/t-CO_2. Similarly, in Guangxi, household biogas is theoretically more cost effective than centralized biogas, MAC of household biogas is calculated to be 56 USD/t-CO_2. In the OII-Scenario, centralized biogas is much cost effective than household biogas in Hebei. In Guizhou, as the *COA* of steel-glass biogas and centralized biogas are two and three times of that of improved cooking stoves, these two options are excluded from constructing the MACC, and improved energy-saving stoves and household biogas become the two most cost-effective options with MACs of -1 and 165 USD/t-CO_2. In Guangxi, the centralized biogas and household biogas are excluded from the MAC analysis, as these two technologies have higher *COA*. Improved cooking stoves are relatively cost effective and the MAC of improved energy-saving stoves is calculated to be 18 USD/t-CO_2.

A negative MAC indicates that a technology is both financially profitable and mitigates CO_2 emissions. The MAC of three technologies –biomass briquette stove, gasifier stove, and solar water heater – are below zero. Some technology options are cost-effective in Full-Scenario but turned out to be not cost-effective when taking into account the implementation factors. For example, with the implementation factors, the MAC of two technologies – solar water heater and improved space heating stove – in Guizhou, are below zero. Whereas biomass briquette stove and gasifier stove turned out to be not cost-effective after taking into account the implementation factors.

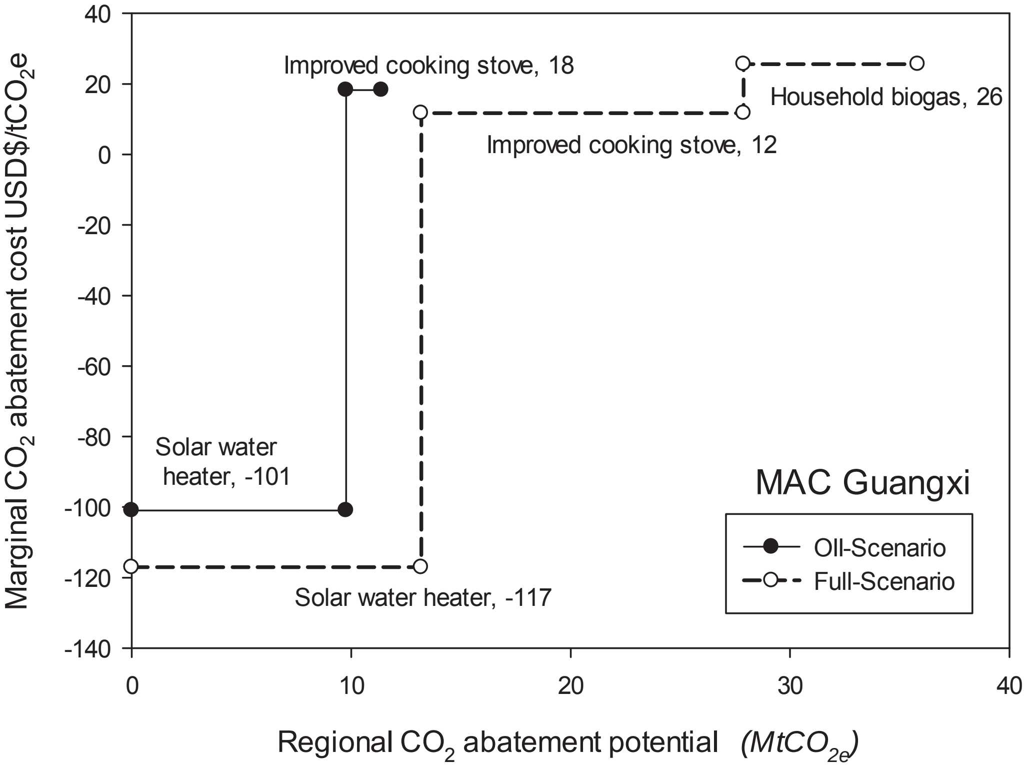
The x-axis of MACC shows the maximum abatement potential. The maximum annual CO_2 abatement potential is estimated to be lower in OII-Scenario than Full-Scenario. In Full-Scenario, the maximum annual CO_2 abatement potential is estimated to be 137, 49, 37 Mt-CO_2 in Hebei, Guizhou and Guangxi. The absolute gap of CO_2 abatement between Full-Scenario and OII-Scenario in Hebei is the largest in the three regions, which is 76 Mt-CO_2/y, followed by Guizhou, which is about 37 Mt-CO_2/y, and the least is Guangxi, which is 26 Mt-CO_2/y. Three factors contribute to the abatement gap: differences of technological option choices in Full-Scenario and OII-Scenario, differences of *AE*, and differences between actual and designed lifetimes.



(a) MAC Hebei



(b) MAC Guizhou



(c) MAC Guangxi

Fig. 7. (a)-(c). MAC curve in three regions at the regional scale, (a) Hebei, (b) Guizhou, and (c) Guangxi (Exchange rate between CNY and USD is 1 CNY = 0.154 USD, and real discount rate = 8 %).

Under the Full-Scenario, the cumulative absolute CO_2 emission abatement from 2015 to 2035 is estimated to be 1,992, 718, and 490 Mt-CO_2 in Hebei, Guizhou and Guangxi. In OII-Scenario, reduction of CO_2 emission is estimated to be 962, 265 and 223 Mt-CO_2. This means that from 2015 to 2035, the overestimated reduction volume between Full-Scenario and OII-Scenario is approximately 1,030, 452, and 267 Mt-CO_2. The relative overestimated CO_2 reduction is calculated as the absolute overestimated CO_2 emission reduction divided by the cumulative CO_2 emissions in Frozen 2015-Scenario. The overestimated CO_2 abatement in the Full-Scenario is calculated to be the highest in Guizhou, 40 %, and 33 % and 32 % in Guangxi and Hebei. The area between the two curves shows the additional costs to reach the maximum annual reduction in the OII-Scenario due to the implementation gaps, which are estimated to be 2.5, 0.5, and 0.2 billion USD per year in Hebei, Guizhou, and Guangxi.

5. Discussion and policy implications

Debates on whether biomass is carbon neutral are discussed in many studies (Johnson, 2009), and only ‘qualified biomass’ in some limited situations could be defined as carbon neutral. Biogas is a key ‘advanced technology’ listed in this study. Biogas is not GHG free, but biogas can reduce GHG emissions by substituting for traditional energy, and it has the co-benefit of air pollutants reduction.

More technological options are included in the Full-Scenario MACC than are selected in the OII-Scenario. This is because the options with higher *COA* but lower *RE* are deducted from constructing MACCs. As discussed above, *r* is a key parameter in the model. As most technologies are under the government subsidy, a higher discount rate is not used in this paper, for example, 15% (Pelenur and Cruickshank, 2012) to 20 % (Zhang et al., 2007) as adopted in some other studies. All results are based on a real discount rate at 8%. A sensitivity analysis is carried out by using discount rate of 15 % and 20 %, as shown in Fig.8.

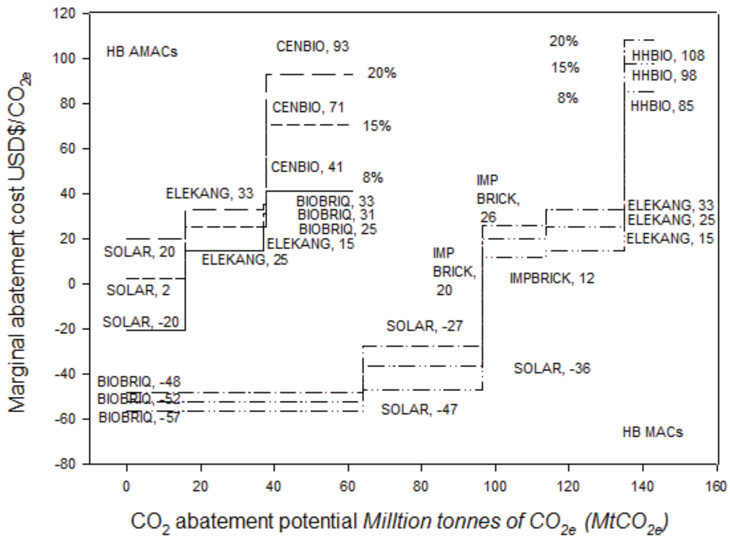


Fig.8. Sensitivity analysis of MAC in Hebei Province w.r.t. the discount rate (r=8 %, 15 %, 20 %).

The metric ranking of technology options does not change with *r*, only the values on the y-axis change due to changes in *r* even though for some technologies, the marginal cost changes from negative to positive. Technologies with shorter lifetimes are less sensitive to changes in *r*, and technologies with longer lifetimes are rather robust to changes in *r*, as shown in Fig.8. Meier and Whittier (1983) make similar findings. The difference in MAC of each abatement technology with and without the implementation factors will be larger when using a higher *r*, the results shown in this study are conservative as an 8 % discount rate is adopted.

Comparing the MECC and MACC calculated in this research with results obtained from other studies, relatively lower abatement costs are presented in this paper. Xiao et al. (2014) calculated abatement costs for 34 energy-saving measures and technologies in China's building sector, finding that the average cost of these technologies is about 19.5 USD/t-CO_2. Their study includes both technological and non-technological measures and only includes commercial energy. In their study, the MAC of most technologies ranges from –50 to 30 USD/t-CO_2 with some as high as 300 USD/t-CO_2. The estimation results in this study is slightly lower because rural household technologies cost less than commercial equipment (Meier, 1982), which has to meet various other performance criteria, the properties of fuel used, mode of stove use and others (Aunan et al., 2013).

6. Conclusions

MACCs can give policy-makers guidance on the maximum abatement potential and costs to reach the abatement target. MACCs will facilitate the setting of subsidy levels to overcome market distortions. This research highlights that the implementation factors will influence the maximum abatement potential. After taking into account the implementation factors, the marginal costs increased for the majority of technologies. The results show that technologies for most space heating technologies are cost negative and the theoretical MAC under perfect implementation is estimated to range from -60 to 15 USD/t-CO_2. Cooking technologies, especially centralized cooking technologies, have a higher marginal abatement cost (MAC) range from 12 to 85 USD/t-CO_2. The MAC in the imperfect implementation scenario is generally higher, from -1 to 15 USD/t-CO_2 for space-heating and from18 to 165 USD/t-CO_2 for cooking technologies. Lack of consideration of the two implementation factors could result in unnecessary government subsidy for costly technologies. The cumulative energy conservation and CO_2 abatement potential will be overestimated if the two implementation factors are not considered. From 2015 to 2035, the cumulative volume of energy savings will be overestimated by 7,766, 3,839, and 2,227 PJ in Hebei, Guizhou, and Guangxi. Cumulative CO_2 abatement from energy consumption related activities is also overestimated, by about 1,030, 452, and 267 Mt-CO_2 from 2015 to 2035, which represent 31 %, 39 % and 32 % of the Frozen 2015-Scenario.

Distributed technologies with lower requirement on skilled labor for installation and maintenance have larger *AE* and longer *t*. For example, household biogas requires professional installation by skilled labors and regular maintenances. Biogas leakage occurs if the digester is not installed properly. The system stops working if the maintenance is not proper. Approaching to energy resources and fuel is another factor that may influence the implementation. For example, in Hebei it is difficult for households to buy biomass fuel nearby.

There are two main ways to improve the implementation of advanced technologies. One is to extend the lifetime of advanced technologies, the other is to make larger substitution of advanced technologies for the traditional reference technology. The government subsidy and rewards for advanced technologies could be made on a yearly basis instead of a lump-sum payment. It is also suggested that distributed technologies should be installed by skilled labor or companies.

Acknowledgments

The authors gratefully acknowledge the financial support of the China Ministry of Science and Technology in the national 973 program: Equity and justice in climate change and regional development (funding code: A.02.12.00301). This research was partly funded by the General Research Fund of the Hong Kong Research Grants Council (14619315).

References:

Amann, M., Cofala, J., Heyes, C., Klimont, Z., Mechler, R., Posch, M., Schöpp, W., 2004. The Regional Air Pollution Information and Simulation (RAINS) Model. Interim Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. www.iiasa.ac.at/rains/review/index.html?sb=10 (accessed 16.09.01).

Aunan, K., Alnes, L.W.H., Berger, J., Dong, Z., Ma, L., Mestl, H.E.S., Vennemo, H., Wang, S., Zhang, W., 2013. Upgrading to cleaner household stoves and reducing chronic obstructive pulmonary disease among women in rural China — A cost-benefit analysis. Energy for Sustainable Development 17, 489-496.

Cai, W., Wan, L., Jiang, Y., Wang, C., Lin, L., 2015. Short-Lived Buildings in China: Impacts on Water, Energy, and Carbon Emissions. Environmental Science & Technology 49, 13921-13928.

Cellura, M., Guarino, F., Longo, S., Mistretta, M., Orioli, A., 2013. The role of the building sector for reducing energy consumption and greenhouse gases: an Italian case study. Renewable Energy 60, 586-597.

Chen, J., Garcia, H.E., 2016. Economic optimization of operations for hybrid energy systems under variable markets. Applied Energy 177, 11-24.

Chen, L., 2011. Mid and large scale biogas projects in Guizhou (In Chinese). China Biogas 29, 27-29.

Dong, H., Dai, H., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., Fujii, M., Masui, T., 2015. Pursuing air pollutant co-benefits of CO_2 mitigation in China: A provincial leveled analysis. Applied Energy 144, 165-174.

Du, L., Hanley, A., Wei, C., 2015. Estimating the Marginal Abatement Cost Curve of CO_2 Emissions in China: Provincial Panel Data Analysis. Energy Economics 48, 217-229.

Du, X., 2011. Research on the Average per Capita Solar Hot Water Consumption in Northern Urban Residence (In Chinese). Building Science 8, 9-11.

Ellerman, A.D., Decaux, A., 1998. Analysis of post-Kyoto CO□ emissions trading using marginal abatement curves. MIT Joint Program on the Science and Policy of Global Change. No. 40. United States. http://hdl.handle.net/1721.1/3608 (accessed 16.09.01).

Gosens, J., Lu, Y., He, G., Bluemling, B., Beckers, T.A.M., 2013. Sustainability effects of household-scale biogas in rural China. Energy Policy 54, 273-287.

GXG, 2009. Guangxi New Energy Development Plan. Guangxi Government.

HBG, 2013. Hebei New Energy 12^{th} Five Year Plan (2011-2015). Hebei government.

Hirst, E., Brown, M., 1990. Closing the efficiency gap: barriers to the efficient use of energy. Resources, Conservation and Recycling 3, 267-281.

Hong, J., Zhang, X., Shen, Q., Zhang, W., Feng, Y., 2017. A multi-regional based hybrid method for assessing life cycle energy use of buildings: A case study. Journal of Cleaner Production 148, 760-772.

Huang, S.K., Kuo, L., Chou, K.-L., 2016. The applicability of marginal abatement cost approach: A comprehensive review. Journal of Cleaner Production 127, 59-71.

IPCC, 2003. Manure Management Methane Emission Factor Derivation for Breeding Swine. Intergovernmental Panel on Climate Change. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf (accessed 2016.09.01).

Jacoboni, C., Reggiani, L., 1983. The Monte Carlo method for the solution of charge transport in semiconductors with applications to covalent materials. Reviews of Modern Physics 55, 645.

Jaffe, A.B., Stavins, R.N., 1994. The energy-efficiency gap: What does it mean? Energy Policy 22, 804-810.

Johnson, E., 2009. Goodbye to carbon neutral: Getting biomass footprints right. Environmental impact assessment review 29, 165-168.

Kesicki, F., Ekins, P., 2012. Marginal abatement cost curves: a call for caution. Climate Policy 12, 219-236.

Klimont, Z., Cofala, J., Bertok, I., Amann, M., Heyes, C., Gyarfas, F., 2002. Modeling particulate emissions in Europe. A framework to estimate reduction potential and control costs, International Institute for Applied System Analysis, Laxenburg. http://pure.iiasa.ac.at/6712/ (accessed 16.09.01).

Li, C., He, L., Cao, Y., Xiao, G., Zhang, W., Liu, X., Yu, Z., Tan, Y., Zhou, J., 2014. Carbon emission reduction potential of rural energy in China. Renewable and Sustainable Energy Reviews 29, 254-262.

Li, F., Cheng, S., Yu, H., Yang, D., 2016. Waste from livestock and poultry breeding and its potential assessment of biogas energy in rural China. Journal of Cleaner Production 126, 451-460.

Lindeburg, M.R., 1992. Engineer-in-training reference manual, eighth ed. Professional Publications Incorporated, Michigan, United States.

McKinsey&Company, 2009a. China's green revolution: prioritizing technologies to achieve energy and environmental sustainability. McKinsey & Company, Beijing. www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/chinas-green-revolution-prioritizing-technologies-to-achieve-energy-and-environmental-sustainability (accessed 2016.09.01).

McKinsey&Company, 2009b. Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Company. www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to

-a-low-carbon-economy (accessed 2016.09.01).

Meier, A.K., 1982. Supply curves of conserved energy, Ph.D. Thesis. California Univ., Lawrence Berkeley Lab. Energy Efficient Buildings Program. Berkeley, United States.

Meier, A.K., Whittier, J., 1983. Consumer discount rates implied by purchases of energy-efficient refrigerators. Energy 8, 957-962.

MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), 2003. Code for design of building water supply and drainage (GB 50015-2009). www.era.com.cn/upload/2016/01/25/14536848872891dtufd.pdf (accessed 2016.09.01).

Mortimer, N.D., Ashley, A., Moody, C., Rix, J., Moss, S., 1998. Carbon dioxide savings in the commercial building sector. Energy Policy 26, 615-624.

NBSC, 2015. National Bureau of Statistics of China. China Statistical Yearbook 2014. China Statistics Press, Beijing. www.stats.gov.cn/tjsj/ndsj/2014/indexeh.htm (accessed 16.09.01).

Nie, H., Kemp, R., 2014. Index decomposition analysis of residential energy consumption in China: 2002–2010. Applied Energy 121, 10-19.

Niu, H., He, Y., Desideri, U., Zhang, P., Qin, H., Wang, S., 2014. Rural household energy consumption and its implications for eco-environments in NW China: A case study. Renewable Energy 65, 137-145.

Pelenur, M.J., Cruickshank, H.J., 2012. Closing the Energy Efficiency Gap: A study linking demographics with barriers to adopting energy efficiency measures in the home. Energy 47, 348-357.

Rehl, T., Müller, J., 2013. CO_2 abatement costs of greenhouse gas (GHG) mitigation by different biogas conversion pathways. Journal of Environmental Management 114, 13-25.

Roden, C.A., Bond, T.C., Conway, S., Osorto Pinel, A.B., MacCarty, N., Still, D., 2009. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmospheric Environment 43, 1170-1181.

Rubin, E.S., Cooper, R.N., Frosch, R.A., Lee, T.H., Marland, G., Rosenfeld, A.H., Stine, D.D., 1992. Realistic mitigation options for global warming. Science 257, 148-149.

Ruderman, H., Levine, M.D., McMahon, J.E., 1987. The behavior of the market for energy efficiency in residential appliances including heating and cooling equipment. The Energy Journal 8, 101-124.

Rypdal, K., Rive, N., Berntsen, T.K., Klimont, Z., Mideksa, T.K., Myhre, G., Skeie, R.B., 2009. Costs and global impacts of black carbon abatement strategies. Tellus B 61, 625-641.

Rehl, T., Müller, J., 2013. CO 2 abatement costs of greenhouse gas (GHG) mitigation by different biogas conversion pathways. Journal of Environmental Management 114, 13-25.

Schipper, L., Bartlett, S., Hawk, D., Vine, E., 1989. Linking life-styles and energy use: a matter of time? Annual Review of Energy 14, 273-320.

Streets, D.G., Gupta, S., Waldhoff, S.T., Wang, M.Q., Bond, T.C., Yiyun, B., 2001. Black carbon emissions in China. Atmospheric Environment 35, 4281-4296.

Treasury, H.M.s., 2003. UK membership of the single currency: An assessment of the five economic tests. Convergence. www.hm-treasury.gov.uk (accessed 16.09.01).

UNFCCC, 2013. AMS-I.I.: Biogas/biomass thermal applications for households/small users - Version 4.0. United Nations Framework Convention on Climate Change. https://cdm.unfccc.int/methodologies/DB/3WJ6C7R0JFA62VYA2Z2K6WE1RK1PXI(accessed 16.09.01).

Vogt-Schilb, A., Hallegatte, S., 2011. When starting with the most expensive option makes sense: Use and misuse of marginal abatement cost curves, World Bank Policy Research Working Paper Series. http://dx.doi.org/10.1596/1813-9450-5803 (accessed 16.09.01).

Xiao, H., Wei, Q., Wang, H., 2014a. Marginal abatement cost and carbon reduction potential outlook of key energy efficiency technologies in China′ s building sector to 2030. Energy Policy 69, 92-105.

Yang, X., Teng, F., Wang, G., 2013. Incorporating environmental co-benefits into climate policies: A regional study of the cement industry in China. Applied Energy 112, 1446-1453.

Yau, Y.H., Hasbi, S., 2013. A review of climate change impacts on commercial buildings and their technical services in the tropics. Renewable and Sustainable Energy Reviews 18, 430-441.

Yuan, B., Ren, S., Chen, X., 2015. The effects of urbanization, consumption ratio and consumption structure on residential indirect CO_2 emissions in China: A regional comparative analysis. Applied Energy 140, 94-106.

Yuan, X., Zhang, M., Wang, Q., Wang, Y., Zuo, J., 2017. Evolution analysis of environmental standards: Effectiveness on air pollutant emissions reduction. Journal of Cleaner Production 149, 511-520.

Zhang, P., Jia, G., Wang, G., 2007. Contribution to emission reduction of CO_2 and SO_2 by household biogas construction in rural China. Renewable and Sustainable Energy Reviews 11, 1903-1912.

Zhang, L., Zhou, J., 2016. The effect of carbon reduction regulations on contractors' awareness and behaviors in China's building sector. Journal of Cleaner Production 113, 93-101.

Zhang, L.X., Wang, C.B., Song, B., 2013. Carbon emission reduction potential of a typical household biogas system in rural China. Journal of Cleaner Production 47, 415-421.

Zhang, X., Luo, L., Skitmore, M., 2015. Household carbon emission research: an analytical review of measurement, influencing factors and mitigation prospects. Journal of Cleaner Production 103, 873-883.