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An analysis of the costs of energy saving and CO2 mitigation in rural households in China

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Abstract

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Key words:
Energy saving technology, cost estimation, rural households, China
JEL classification:
Q41, Q42, Q54

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

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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 (Cellura et al., 2013; Nie and Kemp, 2014). In China, residential energy consumption consists of roughly 11% of the country's total (Nie and Kemp, 2014; Yuan et al., 2015). 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 (Nie and Kemp, 2014; 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, which is referred to as the 'energy efficiency gap' (Schipper et al., 1989; Hirst and Brown, 1990; Li et al., 2014). Energy efficiency technologies that are financially cost-effective might not be as widely adopted by potential users as expected, and, as a result, actual technology diffusion rates will be lower than the optimal rates (Jaffe and Stavins, 1994). In this paper, we investigate the effect of imperfect technology adoption and implementation on carbon emissions mitigation and abatement costs in rural Chinese households.

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 (Nie and Kemp, 2014; Xiao et al., 2014). In addition, rural buildings are estimated to account for 33% of the CO_2 mitigation potential in the entire building sector in China (Xiao et al., 2014). Researchers usually focus on urban residential or commercial buildings (i.e., Mortimer et al., 1998; Hong et al., 2017), although their mitigation 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 mitigation effects of policy regulations and Yuan et al. (2017) who looked 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 mitigation 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 mitigation 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), and they instead 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) (Xiao et al., 2014), and the uncertainty behind this assumption has rarely been discussed.

Finally, 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 mitigation volume and mitigation cost are quantified accordingly. We also note and discuss regional differences.

This paper is structured as follows: Following the Introduction, the research methodology is given in Section 2. Section 3 describes the data collection survey. Marginal cost curves for energy conservation and greenhouse gas (GHG) mitigation are presented in Section 4. A sensitivity analysis is carried out and weaknesses are discussed in Section 5. Lastly, Section 6 gives the conclusions.

2. Research methodology

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 mitigation 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 metal stove, household biomass gasifier stove, biomass briquette stove, and elevated huokang – a heated bed platform. Solar water heaters serve as a mitigation technology for water heating.

The reference technology refers to the traditional technology, which is replaced by mitigation 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 it is a grounded Huokang. The reference technology for water heating is an electric water heater.

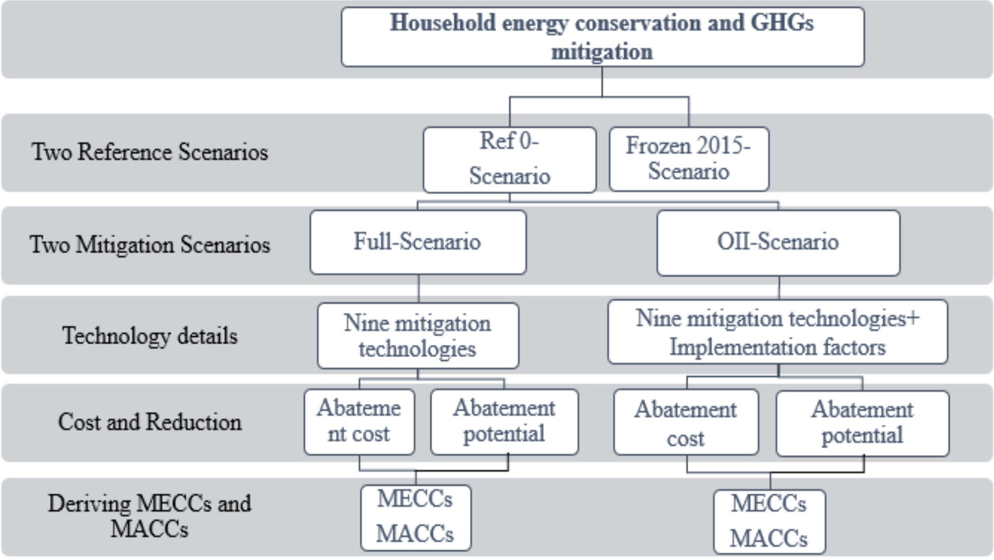


Fig.1. Analysis framework of this study.

We calculate the mitigation cost and mitigation potential for each technology option as the incremental cost of the mitigation technology replacing the reference technology. Unit energy conservation cost (*COE*) is defined as the cost of saving 1 kg coal equivalent 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 x-axis of a MACC shows the abatement level; the y-axis shows the MAC.

The energy efficiency technologies can only be adopted by households who are not currently using these devices. We estimate the maximum energy conservation potential 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.

Four scenarios are used this research (Table 1). Ref 0-Scenario is the Reference Scenario, in which only reference technologies are adopted. It has the highest energy consumption and emission level. 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. The other is due to the lower adoption rate AE. In OII-Scenario, AE is lower than 100% for most options. In Ref 0-Scenario and Full-Scenario, AE ideally equals to 100%.

Table 1

Descriptions and two implementation factors defined in four scenarios.

Scenario	**Descriptions**	**Lifetime of device (*t*)**	**Adoption efficiency (*AE*)**
Ref 0-Scenario	Only reference technology is adopted	Designed lifetime of reference technology	100%
Frozen 2015-Scenario	Shares of current technologies keep constant to 2035	Predicted median lifetime of mitigation technology	Observed *AE* in field survey
Full-Scenario	Mitigation technologies at maximum adoption, gradually from the lowest MAC to the highest	Designed lifetime of mitigation technology	100%
OII-Scenario	Imperfect implementation factors on Full-Scenario	Predicted median lifetime of mitigation technology	Observed *AE* in field survey

Fig. 2 illustrates the relationship among the four 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 BD-BC, equal to the length of CD. The cumulative reduction gap is the area between the two lines, shown as the area of CDE.

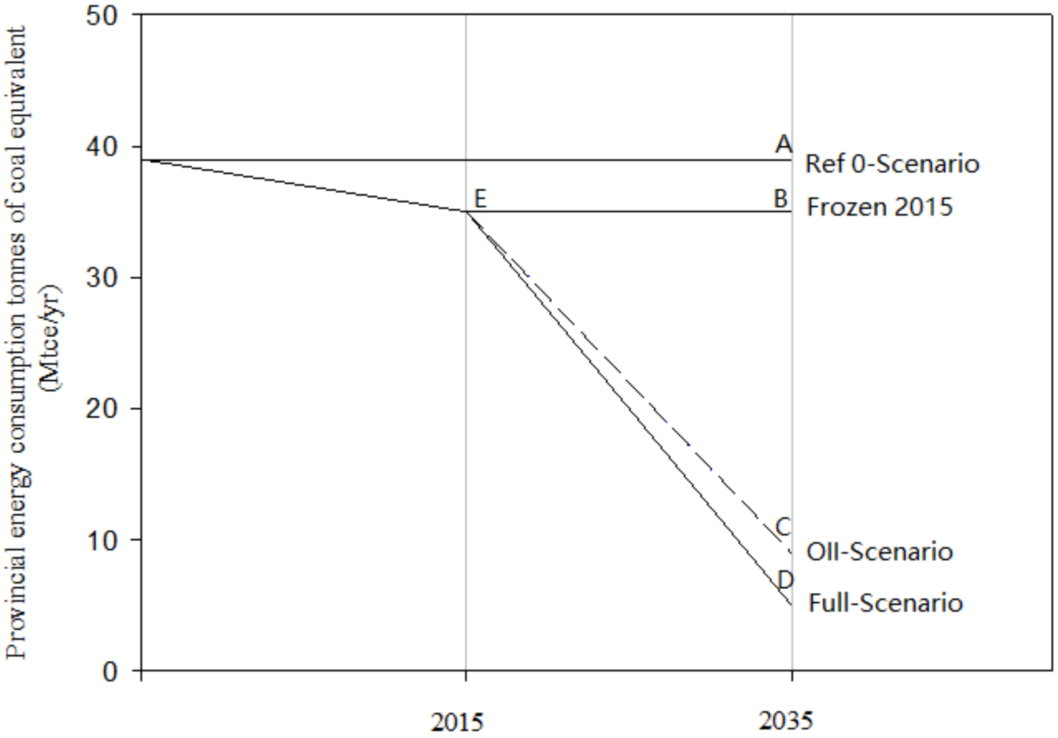


Fig.2. Illustration of the four scenarios defined in this study.

Variable names used in this paper are summarized in Table 2.

Table 2

Summary of variable names

Variable	**Description**
COE	Annualized energy conservation cost of 1 kg coal equivalent
COA	Annualized abatement cost of 1 unit CO_2 equivalent
ΔEC	Energy conservation per household at the technologically maximum potential, kgce/y
AE	Adoption efficiency rate, %
NPV	Net present value in basic year 2015, USD
r	Discount rate, %
CRF	Annuity cost factor
EF	Emission factor gCO_2/kg fuel
FC	Fuel consumption, kgce
RE	Removal efficiency, %

d	Annual working days of biogas digester
v	Daily biogas generation rate, %
$\boldsymbol{\eta}$	Thermal efficiency of biogas cooker, %
h	The net calorific value of biogas, about 20,935 kJ/m^3
B	Maximum methane producing capacity for manure produced by swine, m^3 CH_4 per kg of VS excreted
MCF	Lagoon methane conversion factor calculated by IPCC
MS	Fraction of manure handled in system annually, %
$\boldsymbol{VS_{site}}$	Onsite daily volatile solid excreted for swine, kg
DS	CH_4 density (0.00067 t/m^3 at room temperature (20ºC) and 1 atm pressure)
$\boldsymbol{W_{site}}$	Average animal weight of a defined livestock population at the project site
$\boldsymbol{W_{default}}$	Average weight defaulted by IPCC in calculation, kg
c	Specific heat of water, 4.20 kJ/(kg°C)
Hv	Latent heat of vaporization at atmospheric pressure, 2,257.2 kJ/kg
Temp1	Original water temperature before heated, assumed to be the local temperature, ℃
Temp2	Water temperature after heated, data from the field survey, ℃
$\boldsymbol{\alpha}$	Shape parameter of Weibull distribution
$\boldsymbol{\lambda}$	Scale parameter of Weibull distribution
n	Mitigation technology
t	Lifetime of technology
hh	Household
i	Province
ref	Reference technology
RP	Household scale, people per household

2.2 Calculations of marginal energy conservation cost and marginal abatement cost

The additional cost and abatement potentials are estimated by comparing the advanced technology and the reference technology. 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 equation (1).

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

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; $\Delta EC_{n,hh,i}$ 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 equation (2).

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

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. Thus the discount rate could be adjusted to be lower. Thus 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. AE denotes the adoption efficiency of technology, which is the annual serving days of a technology divided by 365. 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 study 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 lifetime of equipment. We then use Equation (1) 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 equation (3).

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

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 equation (4).

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

The range of t is between the observed age and the designed lifetime for each censored sample. Equation (1) is calculated in these cases by simulating 2000 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. Thus 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 marginal energy conservation cost of technology n denoted by $MECC_n$ is calculated by equation (5):

$$MECC_{n,i} = \frac{\overline{COE_n} \cdot \Delta EC_n - \overline{COE_{n-1}} \cdot \Delta EC_{n-1}}{\Delta EC_n - \Delta EC_{n-1}} \qquad (5)$$

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 mitigation based on energy conservation in units of USD/t-CO_2. COA_n, can be calculated at the household level using equation (6).

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

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 mitigation by adopting advanced technology divided by emissions from the reference technology when meeting the same energy demands, as calculated by equation (7).

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

EF_n denotes the emission factors of each mitigation 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.

We compute the average unit CO_2 abatement cost, $\overline{COA_n}$, in a similar way to COE The MAC of technology n can be calculated based on equation (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.

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

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 equation (9).

$$EC = \nu \cdot d \cdot h \cdot \eta \tag{9}$$

where, *EC* denotes for heat generation by biogas; ν is the daily biogas generation rate (m^3/d), which is estimated based on household number, averaged meals need daily, and 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; *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 3. Two 1000 m^3, a 400 m^3 and a 90 m^3 systems were surveyed in this study.

Table 3
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 equation (10).

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

where d is the working days of the biogas system annually; 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 equation (11).

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

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 equation (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 can be calculated by equation (12).

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

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/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/person per day by a survey study carried out by Du (2011). We obtained the rough data of households on their daily hot water consumption, including washing, bathing and put an adjustment coefficient of 0.7 on the national standard, which is 28 kg/person per day. c is the specific heat of water, 4.20 kJ/(kg°C); Hv is the latent heat of vaporization at atmospheric pressure, 2257.2 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, we asked for their consumption of different fuels and electricity – both commercial and non-commercial fuels were recorded. Three end-use services are distinguished, which are cooking, water heating and space heating. We also recorded the technologies adopted by the household. Third, initial costs, operation and maintenance costs, and fuel costs are included in the questionnaire. Finally, we requested specific information for determining the implementation factors: the frequency of adoption annually and the lifetime 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 4**, which is used for calculating energy consumption and emission level in Frozen 2015-Scenario. Installed ownership indicates households who installed the technology. 2015O 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. 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 4
Ownership of energy-saving technologies in three regions in 2015 (sets/100 households).

End-use service	**Energy-saving technology**	**Hebei**		**Guizhou**		**Guangxi**	
		Installed	2015O	Installed	2015O	Installed	2015O
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

We use data on current centralized biogas users from previous studies and government reports, as shown in **Table 5**.

Table 5
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 million households respectively 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. Thus 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). Thus 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) we assume constant energy prices. 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 mitigation 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 respectively. It is a description of the field survey results. The two figures illustrate the energy consumption level and CO_2 emission level in 2015 respectively.

In Fig.4 the household energy consumption levels of the three end-use services in the Ref 0-Scenario in 2015 is illustrated as the total column height. It is the sum of energy saving relative to the Ref 0-Scenario 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.

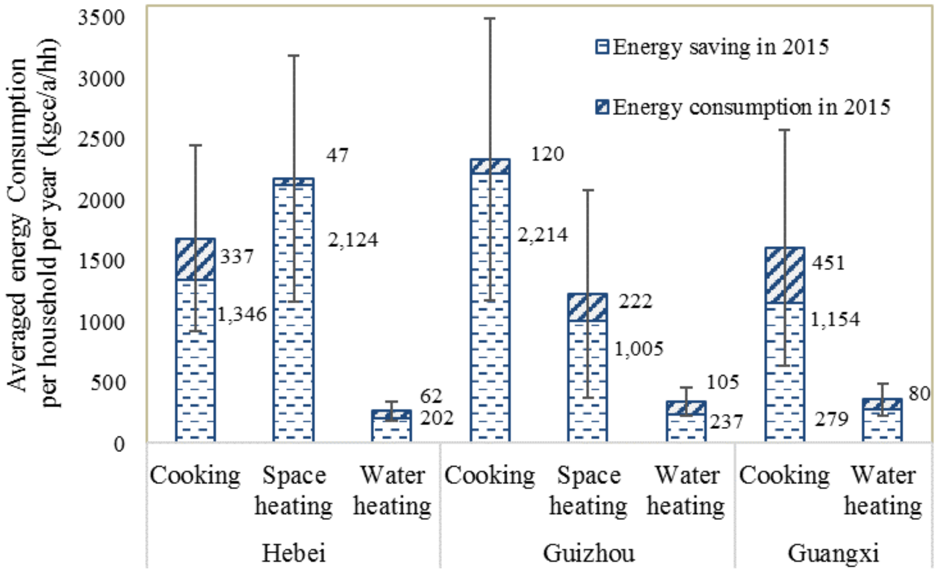


Fig.4. Energy consumption and energy-saving from existing technologies per household in 2015 relative to the Ref 0-Scenario by cooking, space heating and water heating in Hebei, Guizhou and

Guangxi (±Standard Deviation (S.D.)).

The annual CO_2 emission level per household and annual CO_2 mitigation by 2015 are illustrated in Fig.5. The bar height shows the CO_2 emission level in Ref 0-Scenario. 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 6293±2400 kg-CO_2. This number is much lower in Guizhou – 3155±1008 kg-CO_2. Emissions from cooking are the highest in Guangxi in 2015, followed by Hebei and Guizhou.

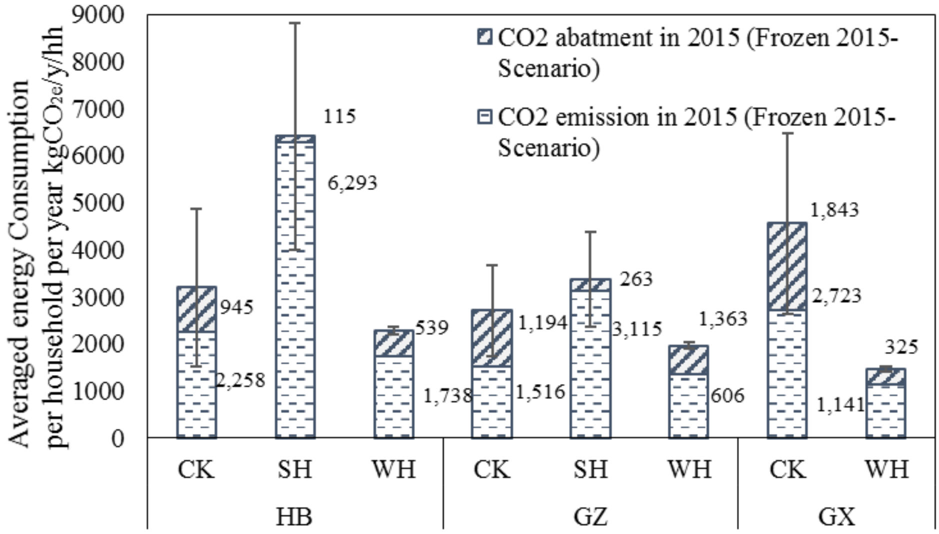
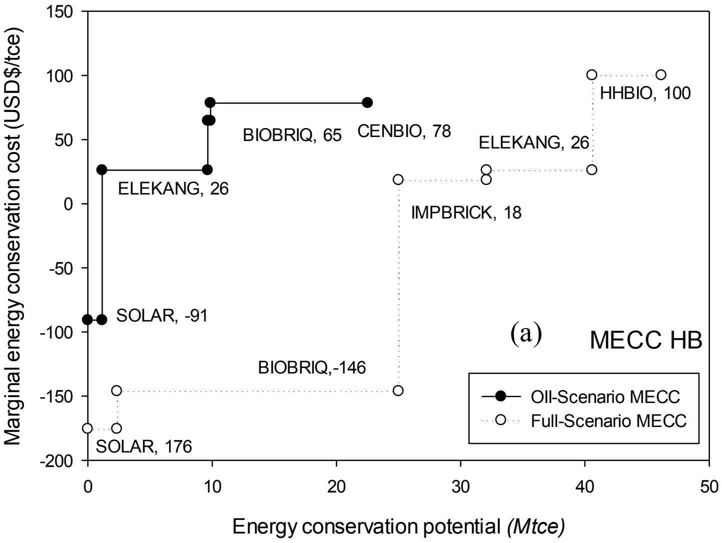


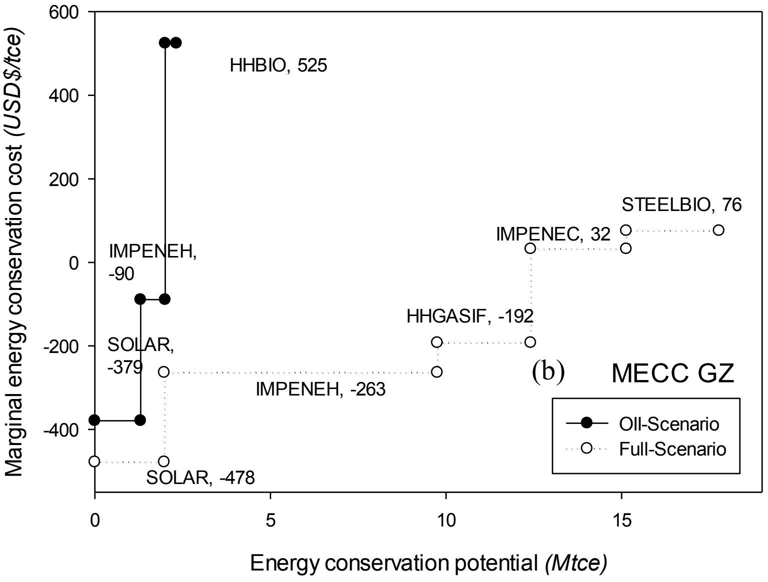
Fig. 5. CO_2 emission and CO_2 mitigation per household from existing technologies in 2015 by cooking, space heating and water heating in Hebei, Guizhou, and Guangxi (± Standard Deviation (S.D.)).

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 -478 and 100 USD/tce. 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 mitigation technologies and MECC were changed. The technology energy saving cost based on the MECC in OII-Scenario ranges between -412 to 525 USD/tce.

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 46.45, 17.89, and 12.54 Mtce respectively in Hebei, Guizhou and Guangxi. In OII-Scenario, the maximum annual energy conservation potential in the three regions is 22.68, 2.47 and 2.78 Mtce, respectively. The gap of annual energy conservation between Full-Scenario and OII-Scenario is thus 23.77, 15.42 and 9.76 Mtce, respectively.





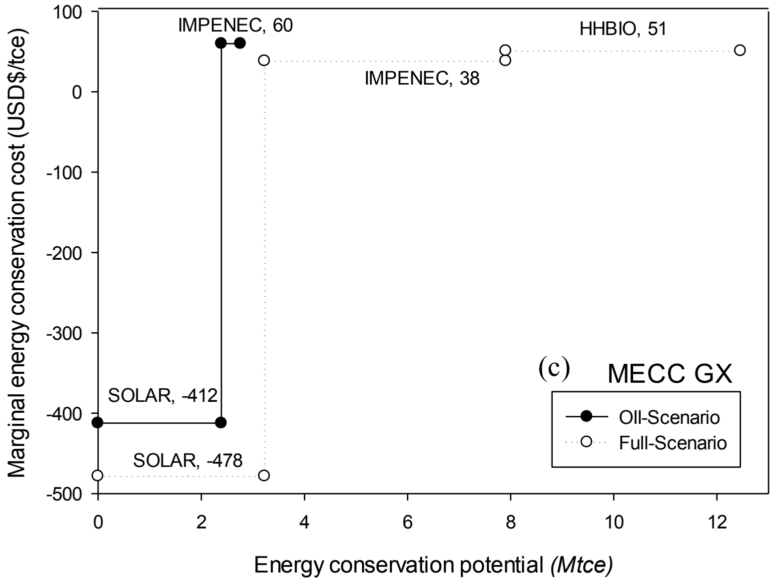


Fig. 6. (a)-(c). MECC in the three provinces at the regional scale (Exchange rate between CNY and USD is 1 CNY = 0.154 USD, and real discount rate = 8%).

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, we see that the MACC and MECC are highly consistent. The reason is that CO_2 mitigation 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 mitigation technologies are re-ranked on the MACCs. The marginal cost of mitigation 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 mitigation 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 small 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 energy-saving 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, respectively. In Guangxi, the centralized biogas and household biogas are excluded from the MAC analysis, as these two technologies have higher *COA*. Improved energy-saving 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 not be 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 metal 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 mitigation potential. The maximum annual CO_2 mitigation potential is estimated to be lower in OII-Scenario than Full-Scenario. In Full-Scenario, the maximum annual CO_2 mitigation potential is estimated to be 137, 49, 37 Mt-CO_2 in Hebei, Guizhou and Guangxi, respectively. The absolute gap of CO_2 mitigation 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. To exclude the influence of the population scale, the relative gap is calculated in each region, which is the absolute reduction gap between the Full-Scenario and OII-Scenario divided by the annual CO_2 emission level in 2015. The relative reduction gap from the largest to the lowest is 76% in Guizhou, 73% in Guangxi and 57% in Hebei, respectively. Three factors contribute to the mitigation gap: differences of technological option choices in Full-Scenario and OII-Scenario, differences of *AE*, and differences between actual and designed lifetimes.

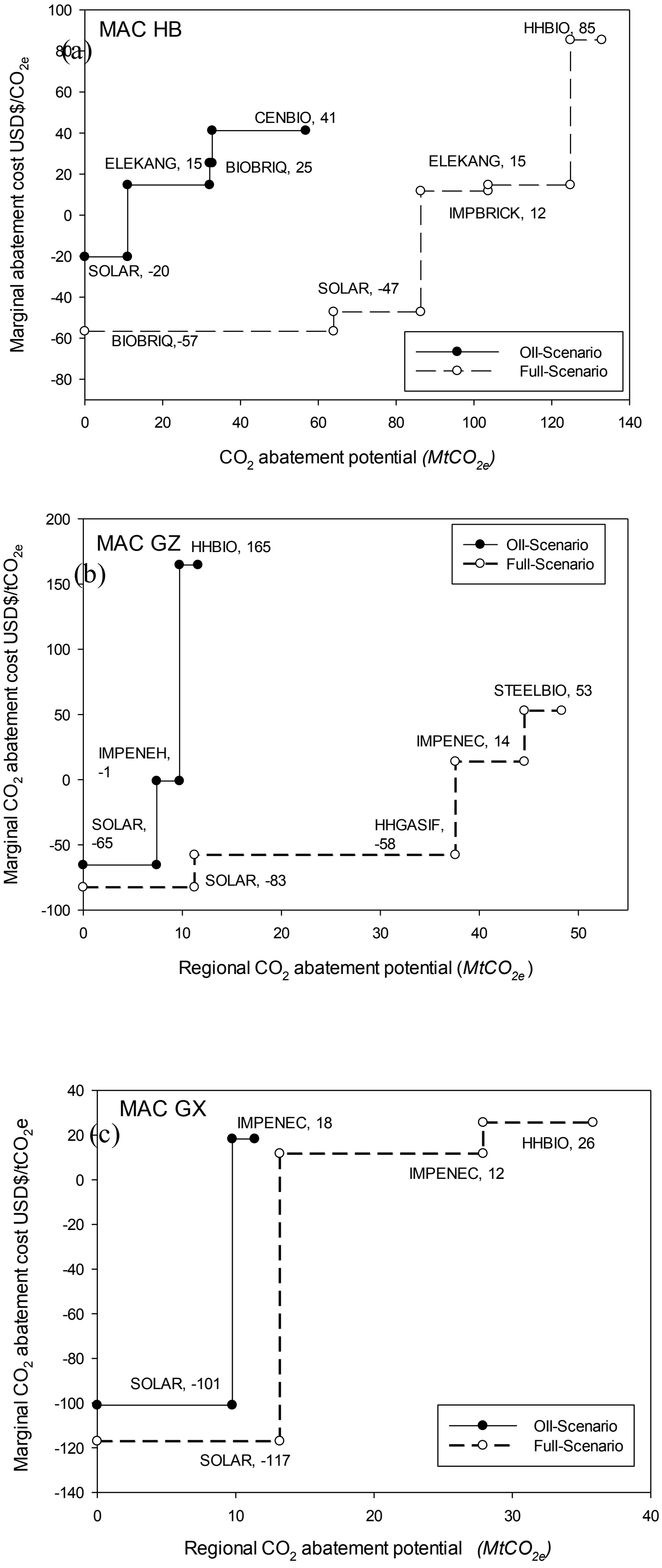


Fig. 7. (a)-(c). MAC curve in three regions at the regional scale (Exchange rate between CNY and USD is 1 CNY = 0.154 USD, and real discount rate = 8%).

Under the Full-Scenario, the cumulative absolute CO_2 emission mitigation from 2015 to 2035 is estimated to be 1,992, 718, and 490 Mt-CO_2 in Hebei, Guizhou and Guangxi, respectively. 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 0-Scenario. The overestimated CO_2 mitigation in the Full-Scenario is calculated to be the highest in Guizhou, 40%, and 33% and 32% in Guangxi and Hebei, respectively. 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, respectively.

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 in addition 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, we are not using a higher discount rate, for example, 15% to 20% as adopted in some other studies (Pelenur and Cruickshank, 2012; Zhang et al., 2007). All results are based on a real discount rate at 8%. We carried out a sensitivity analysis using discount rate of 15% and 20%, as shown in Fig.8.

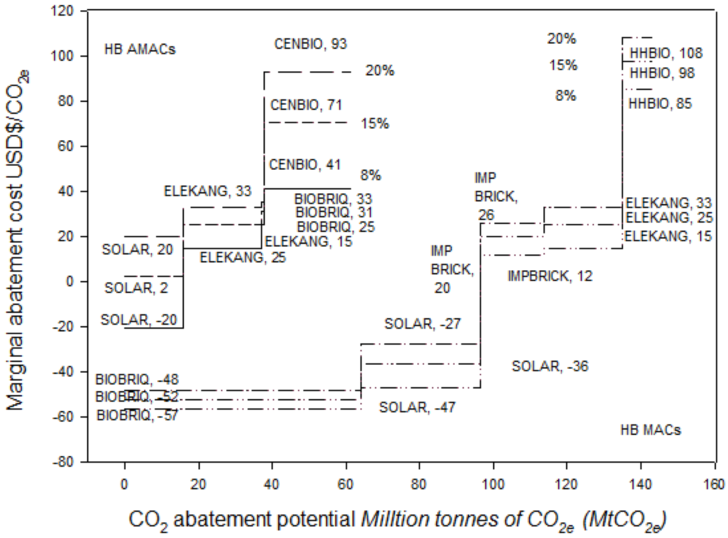


Fig.8. Sensitivity analysis of MAC in Hebei Province w.r.t. the discount rate (r=8%, 15%, 20%).

The metric ranking of technology options does not change as we change *r*, thus 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 mitigation technology with and without the implementation factors will be larger when using a higher *r*, thus the results shown in this study are conservative as we adopt an 8% discount rate.

Comparing the MECC and MACC calculated in this research with results obtained from other studies, we estimate relatively lower abatement costs. 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, which has to meet various other performance criteria (Aunan et al., 2013; Meier, 1982).

MACCs can give policy-makers guidance on the maximum abatement potential and costs to reach the abatement target. Also 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. Also after taking into account the implementation factors, the marginal costs increased for the majority of technologies. Some cost-effective technological options in Full-Scenario are in fact not cost-effective when the implementation factors are considered. Lack of consideration of the two implementation factors could result in unnecessary government subsidy for costly technologies.

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. We also suggest that distributed technologies should be installed by skilled labor or companies.

6. Conclusions

MECC and MACC are two basic economic tools for the analysis of the cost-effectiveness of a set of technological options to find the optimal pathway toward an energy and CO_2 emission reduction target. This research is the first attempt to construct a regional MECC and MACC using energy survey data and detailed technology information in rural China. We quantify the imperfect implementation factors of household technology adoption. The MECC and MACC with and without involving the two implementation factors are constructed for Hebei, Guizhou, and Guangxi provinces and the results compared. The major conclusions of this research are as follows.

The inclusion of implementation factors will change the cost-effectiveness of the majority of mitigation 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.

The cumulative energy conservation and CO_2 mitigation potential will be overestimated if we do not consider the two implementation factors. From 2015 to 2035, the cumulative volume of energy savings will be overestimated by 265, 131, and 76 Mtce in Hebei, Guizhou, and Guangxi, respectively. Cumulative CO_2 mitigation from energy consumption related activities is also overestimated, by about 1030, 452, and 267 Mt-CO_2 from 2015 to 2035, which represent 31%, 39% and 32% of the frozen 2015 scenario, respectively.

If the current implementation factors remain constant until 2035, the annual maximum CO_2 mitigation potential is estimated to be 57, 11 and 10 Mt-CO_2/y in Hebei, Guizhou and Guangxi, respectively. To reach this mitigation target, the additional costs are estimated to be approximately 2529, 483, and 234 million USD annually.

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Supporting information

Table S1

GHGs emission factor in previous studies and used in this paper

Technology	Fuel	Unit	CO$_2$ emission factor	In this study
			g/unit fuel if not specific	
Brick stove	Corn residues	kg	1,247 (Jingjing et al., 2001); 1,130 (Zhang et al., 2000); 1,490 (Shen et al., 2010)	1,247
	Wood/brush	kg	1,520 (Zhang et al., 2000)	1,520
Biogas stove	Biogas	m^3	1,173 (Cao et al., 2006)	1,173
Residential coal stove in north China	Bituminous coal Chunk	kg	2,290, 2,510, 2,050, 2,770 (Zhang et al., 2000)	2,400
Two-way use biomass briquette stove	Biomass briquette (same as industry biofuel)	kg	1,203 (Wang et al., 2013)	1,203
Solar		m^2	0	0
Biomass gasifier stove (with secondary air supplement)	Biomass pellet	MJ	1.7 (Bhattacharya and Salam, 2002)	1.7
Electricity (power grid)	Hebei	kWh	1,060 (Cuimei and Quansheng, 2014)	1,060
	Guizhou	kWh	707 (Cuimei and Quansheng, 2014)	707
	Guangxi	kWh	502 (Cuimei and Quansheng, 2014)	502

Table S2

Technology overall efficiency (%) by fuel type and technology type

Technology	Energy fuel	Overall thermal efficiency	In this study
For cooking			
3-stone open fire		8-10% (Shen et al., 2015), (Zhang et al., 2009) 13.7-14.9% (Jetter et al., 2012)	11.65% (Med.)
Traditional cooking brick stove	Wood	18% (Bentsen et al., 2014)	18%
	Agricultural waste	15% (Bentsen et al.,	15%

Improved cooking brick stove	Wood	2014) 38% (Bentsen et al., 2014) 23.96% (Zhang et al., 2000) 14.41% (Zhang et al., 2000)	23.96%
	Agricultural waste	35% (Bentsen et al., 2014)	35%
Household Biogas stove	Biogas	45–57.4% (Grima-Olmedo et al., 2014)	45%
Biogas stove in large project	Biogas	>55% (NSDBS, 2001)	55%
Residential electric appliance[1]	Electricity	60-85% (NSMC, 2008)	72.5%
Traditional metal stove (Coal and wood-saving stove with flue)	Coal/wood/brush/straws	14% (Bentsen et al., 2014) 14.27 (Zhang et al., 2000) 17.64 (Zhang et al., 2000) 27.23% (Zhang et al., 2000) 37.11% (Zhang et al., 2000)	17.64%
Improved metal stove (Coal and wood-saving stove with flue)	Coal/wood/brush/straws	20-30% (Shen et al., 2015; Statistics, 1997) 25% (Chen et al., 2006) 16-36% (Raman et al., 2014)	25%
Biomass gasifier stoves	Biomass pellet fuel	37% (Shen et al., 2015) 35-41% (Zhang et al., 2009) 9.58-23.2% (Fan et al., 2010) 40% * 42 (Tryner et al., 2014)	37%

For water heating			
Solar water heater	Solar energy	46-54% (Chang et al., 2004)	50%
For space heating			
Traditional brick stove	Grounded Huokang	10.68% (Zhuang et al., 2009) 13.13 (Zhang et al., 2000)	11.91%
	Elevated Huokang	31.44% (Zhuang et al., 2009)	31.44%
Improved brick stove	Grounded Huokang	25% (Jingjing et al., 2001)	25%
	elevated Huokang	35% (Jingjing et al., 2001)	35%
Biomass briquette stove	Biomass briquette	72.56% (Roy and Corscadden, 2012) 70% (NEN, 2011)	71.28% (Avg.)
Biomass gasifier stoves	Biomass pellet fuel	37% (Shen et al., 2015) 35-41% (Zhang et al., 2009) 23.2% (Fan et al., 2010) 42% (Tryner et al., 2014)	37% (Med.)
Electric appliance	Electricity	95% (NSTC, 2012)	95%
Traditional metal stove for space heating	Coal/wood/brush/straws	14% (Bentsen et al., 2014) 14.27 (Zhang et al., 2000) 17.64 (Zhang et al., 2000) 27.23% (Zhang et al., 2000) 37.11% (Zhang et al., 2000)	17.64% (Med.)
Improved metal stove for space heating (Coal and wood-saving stove)	Coal/wood/brush/straws	60% (Shen et al., 2015; Statistics, 1997)	60%

Table S3

Estimation of the construction costs for non-commercial technologies adopted in rural China (material prices based on 2015)

Technology	**Material consumption**	**Material unit cost (Yuan)**			**Material consumption**	**Device cost (Yuan/set)**		
		HB	GZ	GX		HB	GZ	G
Grounded brick Huo Kang (2m length×3 width)	Cement (Yuan/t)	400	450		0.025-0.04t	160		
	Brick (Yuan/piece)	0.5	0.7		45-60 pieces	225		
	Sand (Yuan/t)	200	300		0.1-0.15t	40		
	Construction material in total					425		
	Labor cost (Yuan/d)	150	100	100	2	300		
	Total					725		
Elevated Huo Kang (2m length×3 width)	Cement (Yuan/t)	400	450	360	0.3-0.5	160		
	Brick (Yuan/piece)	0.5	0.7		400-500	225		
	Sand, stones etc. (Yuan/t)	200	300		0.15-0.25	40		
	Tile (Yuan/m^2)	20			2.2-2.6	48		
	Construction material in total					473		
	Labor cost (Yuan/d)					300		
	Total					773		
Traditional brick stove(1m×1 m square in HB) 3m×2m in GZ	Cement (Yuan/t)	400	450	360	0.025-0.04	16	14.6	
	Brick (Yuan/piece)	0.5	0.7		45-60	26	36.8	
	Sand, stones (Yuan/t)	200	300		0.15-0.4	25	82.5	
	Construction material in total					67	133.9	
	Labor cost (Yuan/d)	150	100	100	1	150	100	
	Total					219	233.9	
Energy saving brick stove (1m×1m square)	Cement (Yuan/t)	400	450	360	0.025-0.04	18		
	Brick (Yuan/piece)	0.5			45-60	26		
	Sand, stones (Yuan/t)	200			0.-0.15	25		
	Metal grate (Yuan/set)	50			1 set	30		
	Chimney (Yuan/m)	100			3	150		
	Construction material in total					249		
	Labor cost (Yuan/d)					150		
	Total					399		
Household biogas digester (a regular 6 m^3 project)	Cement (Yuan/t)	400	450	360	0.95	380	427.5	34
	Brick (Yuan/piece)	0.5	0.7	0.4	1,000	500	700	40
	Sand, stones (Yuan/t)	200	300	180	1.2	230	360	21
	Pipelines, purifier and other accessories (Yuan/set)	150	150	150	1	150	150	15
	Biogas cooking stove	300	400	400	1	300	400	40
	Construction material in total					1560	2,037.	15

							5	
	Labor cost (Yuan/d)	200	150	150	4.5	900	675	67
	Total					2460	2,712.5	21
Household biogas digester (a regular 8 m^3 project)	Cement (Yuan/t)	400	450	360	1.2	420	540	43
	Brick (Yuan/piece)	0.5	0.7	0.4	1,400	700	980	56
	Sand, stones (Yuan/t)	200	300	180	1.15	230	345	20
	Pipelines, purifier and other accessories (Yuan/set)	1 set	1 set	1 set	1 set	150	150	15
	Biogas cooking stove	300	400	400	1 set	300	400	40
	Construction material in total					1730	2,415	17
	Labor cost	200	150	150	6	1200	900	90
	Total					2930	3,315	2, 9
Household biogas digester (a regular 10, m^3 project)	Cement (Yuan/t)	400	450	360	1.5	600	675	54
	Brick (Yuan/piece)	0.5	0.7	0.4	1,400	700	980	56
	Sand (Yuan/m^3)	130		100	3	390	0	30
	Stones (Yuan/m^3)	30	50	30	3	90	150	90
	Steel (Yuan/kg)	30	50	50	5	150	250	25
	Pipelines, purifier & other accessories (Yuan/set)		200	200	1	200	200	20
	Biogas cooking stove (Yuan/set)	300	400	400	1	300	400	40
	Construction material in total					2,280	2,655	2, 0
	Labor cost (Yuan/d)	200	150	150	7.5	1,500	1,125	1, 5
	Total:					3,780	3,780	3, 5

Table S4

Shape (α) and scale parameter (λ) estimation in fitted Weibull function of the in use year of each mitigation technology

Technology	Hebei		Guizhou		Guangxi	
	α	λ	α	λ	α	λ
Improved brick stove	0.66	6.21				
Household biogas	1.03	5.55	0.84	17.55	1.20	7.11
Steel-glass			0.44	0.64		

biogas				
Improved metal stove	0.88	3.35	1.99	6.08

Table S5

Parameters for estimating the centralized biogas generation and emissions

Parameter	Description	Hebei case study*	Source
Tsite	Annual average temperature	9℃	Local temperature report
TDigester	Digester temperature after heating by solar system or boiler system	25℃	Field survey
EF_{BioGen}	Annual CH_4 emission factor	kg CH_4/y	
d	Working days of biogas system	365 days/y	Field survey
N	Annual swine head amount	3,500 heads	Field survey
Ds	CH_4 density (0.00067 t/m^3 at room temperature (20ºC) and 1 atm pressure)	0.67 kg/m^3	(IPCC, 2006)
MCF	Lagoon methane conversion factor calculated by IPCC	79%	(IPCC, 2006)
MS	Fraction of manure handled in system annually	50%	50% manure used in the system, from field survey
Bo	Maximum methane producing capacity for manure produced by swine, m^3 CH_4 kg^{-1} of VS excreted	0.29 m^3 CH_4/kg VS	(IPCC, 2006)
$VS_{default}$	The default daily volatile solid excreted for swine , kg dry matter per day per head	0.3 kg/hd/d	(IPCC, 2006)
W_{site}	Average animal weight of a defined livestock population at the project site	150 kg	Field survey, farm owner
$W_{default}$	Average weight defaulted by IPCC in calculating VS	28 kg	(IPCC, 2006)

* In Guizhou and Guangxi, the reported output from project manager are adopted.

S6: Calculation method of unit cost

```
clear all
C_data = [];
NC_data = [];
%data = xlsread('Uncertainty.xlsx',7,'A13:Z49');
data = xlsread('solar_sensitivity.xlsx',3,'A8:Z40');
```

```
data_size = size(data);
for i = 1:data_size
        if isnan(data(i,4))
                C_data = [C_data;data(i,:)];
        else
                NC_data = [NC_data;data(i,:)];
        end
end

T_max=10;
a=0.8362172;
b=17.54972;
r=0.08;
rr=0.5;
rrr=0;


cost_real=(C_data(:,5).* (1+C_data(:,8)).^(C_data(:,3)).*
C_data(:,8)./((1+C_data(:,8)).^C_data(:,3)-1)+C_data(:,6));
cost_ideal=(C_data(:,5).* (1+C_data(:,8)).^T_max.* C_data(:,8)./((1+C_data(:,8)).^T_max
-1)+C_data(:,6));
C_UC_temp = (C_data(:,5).* (1+C_data(:,8)).^(C_data(:,3)).*
C_data(:,8)./((1+C_data(:,8)).^C_data(:,3)-1)+C_data(:,6)) ./((C_data(:,21)));
C_UC_ideal_temp = (C_data(:,5).* (1+C_data(:,8)).^T_max.*
C_data(:,8)./((1+C_data(:,8)).^T_max -1)+C_data(:,6)) ./ (C_data(:,22));
DELTA_C_C_temp =
(C_UC_temp-C_UC_ideal_temp)./(log(C_UC_temp)-log(C_UC_ideal_temp)).*log(C_UC_t
emp./C_UC_ideal_temp.*(C_data(:,23)));
DELTA_C_M_temp =
(C_UC_temp-C_UC_ideal_temp)./(log(C_UC_temp)-log(C_UC_ideal_temp)).*log(1./(C_da
ta(:,23)));
S_DELTA_C_C_temp = DELTA_C_C_temp./(DELTA_C_C_temp+DELTA_C_M_temp);
S_DELTA_C_M_temp = DELTA_C_M_temp./(DELTA_C_C_temp+DELTA_C_M_temp);


for i =1:2000
        C_UC(:,i) =C_UC_temp;
        C_UC_ideal(:,i)=C_UC_ideal_temp;
        DELTA_C_C(:,i) = DELTA_C_C_temp;
        DELTA_C_M(:,i) = DELTA_C_M_temp;
        S_DELTA_C_C(:,i) = S_DELTA_C_C_temp;
```

```
    S_DELTA_C_M(:,i) = S_DELTA_C_M_temp;
end
%**************************

NC_data_size= size(NC_data);
NC_UC = zeros(NC_data_size(1),2000);
NC_UC_ideal = zeros(NC_data_size(1),2000);
DELTA_UC_C = zeros(NC_data_size(1),2000);
DELTA_UC_M = zeros(NC_data_size(1),2000);
S_DELTA_UC_C = zeros(NC_data_size(1),2000);
S_DELTA_UC_M = zeros(NC_data_size(1),2000);


k =1;
for i = 1:NC_data_size

    for j = 1:200000
        T_sample = wblrnd(b,a,1,1);
        if T_sample>(NC_data(i,3)) && T_sample<T_max
            NC_UC(i,k) = (NC_data(i,5).* (1+NC_data(i,8)).^T_sample.*
NC_data(i,8)./((1+NC_data(i,8)).^T_sample-1)+NC_data(i,6)) ./    ((NC_data(i,21)));
            NC_UC_ideal(i,k) = (NC_data(i,5).* (1+NC_data(i,8)).^T_max.*
NC_data(i,8)./((1+NC_data(i,8)).^T_max-1)+NC_data(i,6)) ./    (NC_data(i,22));

            DELTA_UC_C(i,k) =
(NC_UC(i,k)-NC_UC_ideal(i,k))./(log(NC_UC(i,k))-log(NC_UC_ideal(i,k))).*log(NC_UC(i
,k)./NC_UC_ideal(i,k)*(NC_data(i,23)));
            DELTA_UC_M(i,k) =
(NC_UC(i,k)-NC_UC_ideal(i,k))./(log(NC_UC(i,k))-log(NC_UC_ideal(i,k))).*log(1/(NC_da
ta(i,23)));

            S_DELTA_UC_C(i,k) =
DELTA_UC_C(i,k)./(DELTA_UC_C(i,k)+DELTA_UC_M(i,k));
            S_DELTA_UC_M(i,k) =
DELTA_UC_M(i,k)./(DELTA_UC_C(i,k)+DELTA_UC_M(i,k));

            k = k+1;
        end

        if k>2000;
            k =1;
```

```
                break
            end
        end

end


UC_T = [];
IdealUC_T=[];
GAP_T =[];
UC = [NC_UC;C_UC];
IdealUC=[NC_UC_ideal;C_UC_ideal];
GAP = UC./IdealUC;
COST=cost_real./cost_ideal;
GAP_mean=mean(mean(GAP));
UCreal_mean=mean(mean(UC));
GAP_std=std(std(GAP));
UCreal_std=std(std(UC));


UC_M = median(median(UC));
IdealUC_M = median(median(IdealUC));
GAP_M = median(median(GAP));
COST_M=median(COST);


for i = 1:data_size
    UC_T = [UC_T,UC(i,:)];
    IdealUC_T=[IdealUC_T,IdealUC(i,:)];
    GAP_T = [GAP_T,GAP(i,:)];
end
y=prctile(UC_T,[2.5,97.5]);
output_UC=[UC_M,y];
y=prctile(IdealUC_T,[2.5,97.5]);
output_IdealUC=[IdealUC_M,y];
y=prctile(GAP_T,[2.5,97.5]);
output_GAP =[GAP_M,y];
y=prctile(COST,[2.5,97.5]);
output_COST=[COST_M,y];
```

```
DELTA_COST=[DELTA_UC_C;DELTA_C_C];
DELTA_MIT=[DELTA_UC_M;DELTA_C_M];
S_DELTA_COST=[S_DELTA_UC_C;S_DELTA_C_C];
S_DELTA_MIT=[S_DELTA_UC_M;S_DELTA_C_M];

DELTA_COST_M = median(median(DELTA_COST));
DELTA_MIT_M = median(median(DELTA_MIT));
S_DELTA_COST_M = median(median(S_DELTA_COST));
S_DELTA_MIT_M = median(median(S_DELTA_MIT));

DELTA_COST_T = [];
DELTA_MIT_T = [];
S_DELTA_COST_T =[];
S_DELTA_MIT_T =[];
for i = 1:data_size
    DELTA_COST_T = [DELTA_COST_T,DELTA_COST(i,:)];
    DELTA_MIT_T = [DELTA_MIT_T,DELTA_MIT(i,:)];
    S_DELTA_COST_T = [S_DELTA_COST_T,S_DELTA_COST(i,:)];
    S_DELTA_MIT_T = [S_DELTA_MIT_T,S_DELTA_MIT(i,:)];
end
y=prctile(DELTA_COST_T,[2.5,97.5]);
output_DELTA_UC_C=[DELTA_COST_M,y];
y=prctile(DELTA_MIT_T,[2.5,97.5]);
output_DELTA_UC_M =[DELTA_MIT_M,y];
y=prctile(S_DELTA_COST_T,[2.5,97.5]);
output_S_DELTA_UC_C=[S_DELTA_COST_M,y];
y=prctile(S_DELTA_MIT_T,[2.5,97.5]);
output_S_DELTA_UC_M=[S_DELTA_MIT_M,y];

C_UC_temp = (C_data(:,5).* (1+r).^(C_data(:,3).*(1+rr)).*
r./((1+r).^C_data(:,3)-1)+C_data(:,6)) ./(C_data(:,21).*(1+rrr));
C_UC_ideal_temp = (C_data(:,5).* (1+r).^T_max.* r./((1+r).^T_max -1)+C_data(:,6)) ./
(C_data(:,22));
DELTA_C_C_temp =
(C_UC_temp-C_UC_ideal_temp)./(log(C_UC_temp)-log(C_UC_ideal_temp)).*log(C_UC_t
emp./C_UC_ideal_temp.*C_data(:,23).*(1+rrr));
DELTA_C_M_temp =
(C_UC_temp-C_UC_ideal_temp)./(log(C_UC_temp)-log(C_UC_ideal_temp)).*log(1./(C_da
ta(:,23).*(1+rrr)));
S_DELTA_C_C_temp = DELTA_C_C_temp./(DELTA_C_C_temp+DELTA_C_M_temp);
S_DELTA_C_M_temp = DELTA_C_M_temp./(DELTA_C_C_temp+DELTA_C_M_temp);
```

```
for i =1:2000
    C_UC(:,i) =C_UC_temp;
    C_UC_ideal(:,i)=C_UC_ideal_temp;
    DELTA_C_C(:,i) = DELTA_C_C_temp;
    DELTA_C_M(:,i) = DELTA_C_M_temp;
    S_DELTA_C_C(:,i) = S_DELTA_C_C_temp;
    S_DELTA_C_M(:,i) = S_DELTA_C_M_temp;
end
%**************************

NC_data_size= size(NC_data);
NC_UC = zeros(NC_data_size(1),2000);
NC_UC_ideal = zeros(NC_data_size(1),2000);
DELTA_UC_C = zeros(NC_data_size(1),2000);
DELTA_UC_M = zeros(NC_data_size(1),2000);
S_DELTA_UC_C = zeros(NC_data_size(1),2000);
S_DELTA_UC_M = zeros(NC_data_size(1),2000);


k =1;
for i = 1:NC_data_size

    for j = 1:200000
        T_sample = wblrnd(b,a,1,1);
        if T_sample>(NC_data(i,3)) && T_sample<T_max
            NC_UC(i,k) = (NC_data(i,5).* (1+r).^T_sample.*
r./((1+r).^T_sample-1)+NC_data(i,6)) ./    (NC_data(i,21)*(1+rrr));
            NC_UC_ideal(i,k) = (NC_data(i,5).* (1+r).^T_max.*
r./((1+r).^T_max-1)+NC_data(i,6)) ./    (NC_data(i,22));

            DELTA_UC_C(i,k) =
(NC_UC(i,k)-NC_UC_ideal(i,k))./(log(NC_UC(i,k))-log(NC_UC_ideal(i,k))).*log(NC_UC(i
,k)./NC_UC_ideal(i,k)*NC_data(i,23)*(1+rrr));
            DELTA_UC_M(i,k) =
(NC_UC(i,k)-NC_UC_ideal(i,k))./(log(NC_UC(i,k))-log(NC_UC_ideal(i,k))).*log(1/(NC_da
ta(i,23)*(1+rrr)));

            S_DELTA_UC_C(i,k) =
DELTA_UC_C(i,k)./(DELTA_UC_C(i,k)+DELTA_UC_M(i,k));
```

```
            S_DELTA_UC_M(i,k) =
DELTA_UC_M(i,k)./(DELTA_UC_C(i,k)+DELTA_UC_M(i,k));

            k = k+1;
        end

        if k>2000;
            k =1;
            break
        end
    end

end
```

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