Greenhouse gas and air pollutants emissions of China's urban residential sector: Analysis on household energy transition

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1. Introduction

In final energy consumption, the building sector is one of the largest energy-consuming sectors, accounting for over one-third globally and is an equally important source of carbon dioxide emissions. The building sector can be divided into residential and service sub-sectors, in which residential sub-sector shares the second or third largest of final energy consumption. Implementation of energy efficient technologies is needed to address the sustainability in household sector. The energy choice of households is crucial to the technology selection. Low-carbon technologies usually are based on advanced energy sources. In an area with limited access to commercial energy resources the low-carbon technologies will be difficult to implement in households. This study looks into the energy transition process caused by socioeconomic development, as well as mitigation potential of carbon emissions in China's household sector.

Several existing studies suggested two types of energy transition models in residential sector -- energy ladder and energy stack (Figure 1). The energy ladder theory assumes that households will move to more sophisticated energy carriers as their income increases. On the other hand energy stack argues that household energy transition does not simply move from one energy source to another. With increasing income, households rather adopt multiple fuel choices and sometime users may switch back to traditional biomass even after adopting modern energy carriers.

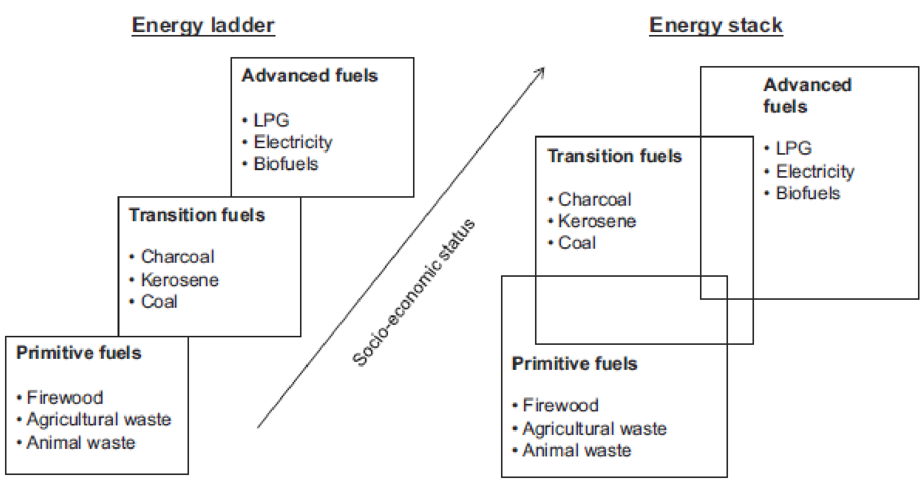

Figure 1. The energy transition process (Van der Kroon B. et al. 2013)

Several studies have identified the socioeconomic driving forces of energy choice behaviour. Education is seen as an important determinant of energy transition process. Barnes et al. and Peng et al. suggested that higher levels of education cause households to use less traditional biomass fuels (i.e. primitive fuels). Availability of household labour also has been found by many researchers as a determining factor for use of traditional biomass fuel in rural area. The household fuel choice also involves gender perspective. Gupta et al., Sathaye et al., and Israel et al. found that a household with more women present would have larger availability of firewood resource. Heltberg et al. introduced that in Guatamala the female population share in households is assumed to specially constrain a switch to modern fuels as "they are mainly responsible for the collection of firewood". Additionally women's income is considered to be an important determinant of modern fuel choice.

Some studies suggest that energy transition is not unidirectional and people may switch back to traditional biomass when a high increase of modern energy price occurs. However, the effect of fuel prices on fuel choice is still under debate. Some scholars suggest that prices are the main factor restricting households to move to modern fuels, while others find fuel prices have little impact on household fuel selection. Income level is another monetary factor that effects on energy transition. In most of the studies household energy choice is found to progress toward modern energy when income level increases. An interesting finding in rural China is that traditional biomass use will rise as income level increases (Zhao et al. 2012). This is contrary to the proposed energy transition theory. Researchers suggested the possible reason is that the basic energy demand has not been fully met in rural regions.

In this study we firstly select socio-economic indicators that potentially effect on household transition process and analyse their co-relations with household energy choice. The future household related CO_2 emission and reduction potential will be estimated using integrated assessment model named AIM/Enduse. The results will provide estimations of household energy share in the future and emission reduction potential brought by socio-economic development. This study can contribute to the existing studies in the following two aspects. One aspect is that most of the integrated assessment models do not consider energy transition process in rural/urban household sector at provincial levels in China while generating emission pathways. This may cause overestimation or underestimation of the emission reduction potential. This study will provide an energy share estimation of household sector in the future and a more accurate emission reduction potential evaluation. Another aspect is that adopting an universal low-carbon technology in different regions is not effective due to socioeconomic gaps across regions. This study will provide tailored implementation plans of low-carbon technologies for regions at various socioeconomic statuses.

This paper is structured into Sections 2, 3, and 4. Section 2 describes the methodology for estimating household energy share and CO_2 emission. Section 3 presents the estimation results. Section 4 summarizes key conclusions and future work.

2. Methodology

2.1 Study subjects and regional approach

There are 31 provincial-level administrative regions in mainland China[1]. The climate in China varies widely, ranging from tropical regions in the south to subarctic areas in the north. China's climactic divide separates the country into northern (central heating) and southern (no central heating) regions, while its economic divide separates it into eastern and western regions (Figure 2). In order to take fully consideration of the above mentioned climate and economic gaps, in the previous studies, we have carried out emission evaluation studies on a regional basis (Xing et al 2015). Several existing studies have pointed out that economic indicators such like income and per capita GDP are principal drivers of household energy choice. In a relatively more developed region the share of commercial energy appear to be higher than other less development regions. In addition, climate also has impact on household energy share. In cold area heating service supported by coal is currently the major application of energy use. While in warm area people consume more energy on electronic appliances. Under such circumstances, the analysis of household energy share is also conducted on a regional basis and efficient technology evaluations are tailored for regions at various socioeconomic statuses.

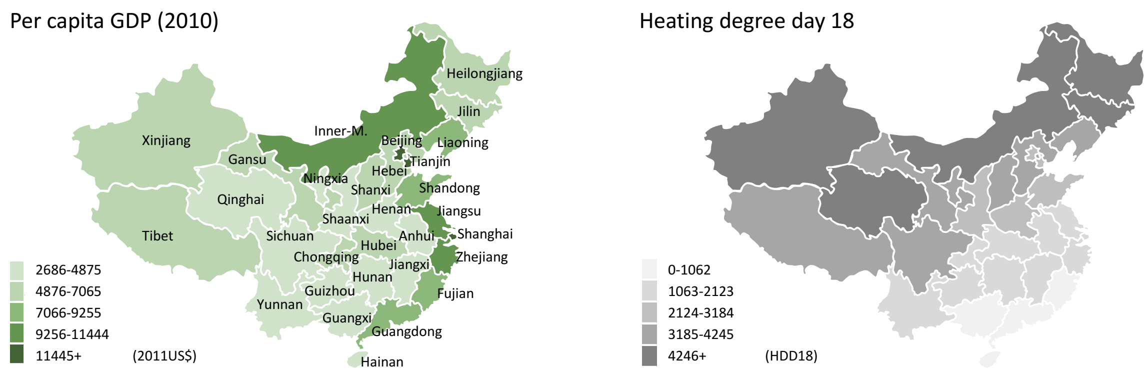

Figure 2. Regional gaps in 31 Chinese regions

2.2 Regression analysis

This study considers energy transition process from transition fuel (coal) to advanced fuels such as LPG and electricity in urban household. For rural household, primitive fuels such as firewood and stalks are also considered. City gas is another major energy carrier in urban household. However, the distribution of city gas network basically depends on city infrastructure rather than choices of households. Therefore city gas is not included in the energy sources in this study. Figure 3 indicates the five subjected energy sources of urban and rural households.

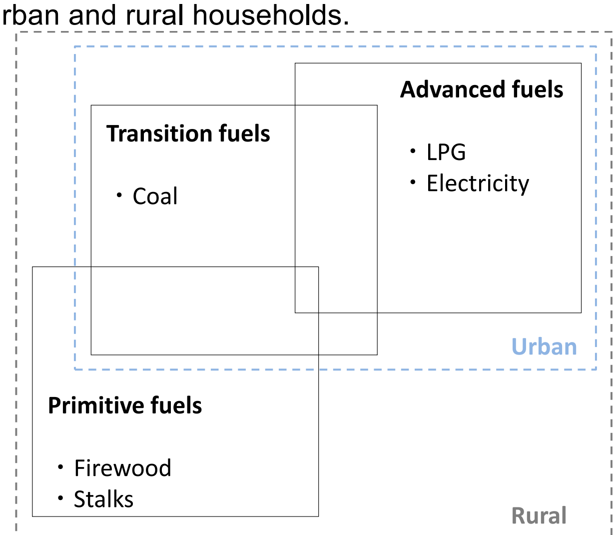

Figure 3. Energy stack in urban and rural China

Van der Kroon et al (2013) summarized the driving forces underlying energy choice behaviour identified in previous studies. Base on their conclusion, 12 socioeconomic indicators -- income, education level, heating degree day 18 (HDD18), HDD dummy ("1" if central heated "0" if not), household size, per capita floor area, dependency, cereal production share, timber production share, coal production share, coal production share dummy ("1" if more than 3% of national total "0" if not) and female share in household, are selected to analyse their co-relations with the energy share. Income and education level are the major indicators which have been suggested to impact on energy choices in almost every literature we reviewed. Heating degree day 18 (HDD18) and a dummy variable (HDD dummy) represents the impacts from climate and central heating system, respectively. In addition to that, we also include per capita floor area in order to examine the impact of heating demand (totally heated area). Household size and age are two influencing indicators that suggested by previous studies. In this study, age indicator is further interpreted into dependency – population ages under 14 and above 65 divided by population ages between 15 to 64. In rural households, traditional biomass such like firewood and stalks are often gathered from the local area. Thus we also consider the biomass resource indicators (e.g. production shares of cereal and timber) as influencing variables. Last but not least, female population share in household explain the impact from gender perspective.

In the next step we use the panel data of the energy source share and 12 variables in 31 regions to conduct the multiple regression analysis. The time period of panel data is from 2000 to 2007[1]. Among those 12 explanatory variables, it is possible that some of them are co-related. Conducting regression analysis on those variables may face the risk of multicollinearity hence effect on the reliability of the results. As a solution, the 12 selected variables are divided into 7 perspectives. The variables in the same perspective are at high risk of multicollinearity and only one variable from each perspective is used to conduct regression analysis at one time. We test all variable combinations from 7 perspectives and take combinations that have the highest determination coefficients as final results. A dummy coefficient is added to each equation in order to calibrate the estimates with statistical data of 2007. Eq. 1 is the regression equation.

$$S_{e,r,t} = \sum_i a_{i,e} X_{i,r,t} + b_e + d_{e,r} \quad (1)$$

where *e* is energy; *r* is region; *t* is year; *i* is socioeconomic perspective; *S* is energy share; a_i is regression coefficients; X_i is value of socioeconomic perspective; b_e is regression intercept; $d_{e,r}$ is base year calibration coefficient. Table 1 summarizes the grouping of perspectives and influencing variables (X) of each energy source.

2.3 Scenario setting

For the model simulation we prepare three scenarios to evaluate the gas emission growth and reduction potential: the Fix (FIX), Business as usual (BaU), and Energy transition (ET) scenarios. In the FIX scenario the technologies can be regarded as frozen: the technology level remains at the base year (2010) level and no efficient technologies are implemented in the future. FIX is designed to offer a baseline picture of how gas emissions will increase without any efficient technology intervention. In BaU,

[1] Since 2008 information of non-commercial energy use is no longer included in the energy statistical yearbook

efficient technologies stored in technology databases are allowed to penetrate the future market without any carbon tax or carbon policy. Traditional technologies compete with efficient technologies over cost-effectiveness, but no carbon pricing is imposed. In general terms, BaU describes an autonomous energy efficiency improvement process for efficient technologies.

The BaU scenario sets no constraint on energy use. In contrast, the ET scenario sets the maximum share of each energy source determined by Equation 1. Energy share ranges from zero to one thus value falls outside of the range will be corrected to the limit value (i.e. zero or one). Table 1 summarizes the definitions of the three scenarios.

Table 1. Summary of explanatory variables (U=Urban; R=Rural)

Perspective	Explanatory variable	Stalks	Firewood	Coal		LPG		Electricity	
		R	R	U	R	U	R	U	R
Development	Income (2011$US)		√	√		√	√	√	√
	Educated in college and higher level	√			√				
Climate	HDD dummy ("1" if central heated "0" if not)				√				
	HDD18	√	√						
Household	Household size (persons/household)					√		√	
Housing	Per capita floor area (m2)								
Age	Dependency ((Age 0-14 + Age 65 and over)/Age 15-64)				√		√		√
Energy resource	Cereal production share	√							
	Timber production share		√						
	Coal production share								
	Coal production dummy ("1" if more than 3% of national total "0" if not)								
Gender	Female share in household (female pop./household)								

Table 2. Scenario definitions

Scenario		**Definition**
Fix (FIX)	·	Future technology efficiency and diffusion ratio fixed at the 2010 level
Business as usual (BaU)	·	Efficient technologies autonomously penetrate the future market (without *Energy transition*)
Energy transition (ET)	·	Efficient technologies penetrate the future market

	· Share of each energy source not to succeed the maximum value estimated in Section 2.2 (with *Energy transition*)

2.4 AIM/Enduse

The AIM/Enduse model is a bottom-up optimization model designed to estimate mitigation potential of sustainable policies (Kainuma et al, 2003; Hanaoka et al, 2015). The country scale AIM/Enduse database has been developed over the past 20 years by researchers from various countries. More recently, the AIM/Enduse study also focuses on regional diversities. We base the present study on the newly developed regional model, AIM/Enduse[China].

In model simulation, AIM/Enduse first determines combinations of technologies with the least total system cost that can satisfy future service demand. Then, the energy and GHG (Greenhouse Gas) emissions caused by the determined technology combination are estimated with information of technology efficiency and emission factors. During the technology selection process, estimated service demands are disaggregated to the energy usage of existing technologies in the base year (2010) and later satisfied by selecting both existing and efficient technologies using the AIM/Enduse model in the target year (2030). For each household device, existing (EXT) technology was assigned low efficiency and one or more technologies (NEW and BAT) were assigned high efficiency. NEW technology is assumed to have a higher efficiency and the best available technology (BAT) is assumed to be the most efficient technology, based on the realistic and currently existing technologies in the mitigation option database.

3. Results

3.1 Household energy share

Figure 4 shows the estimated results of maximum energy share in 31 provinces. Generally the transition from primitive fuel to advanced fuel is observed in both urban and rural areas. For traditional biomass, stalks will still have a certain amount of share in most of the regions while firewood share will drop to a limited level, because, according to regression analysis results in Section 2.2, stalks share is negatively co-related with education level and firewood is negatively co-related income level which caused the significant reduction of energy share. Coal will be completely phased out in urban area and its share in rural area will drop to under 50% in most of the regions. Urban households will gain 100% access to advanced fuels LPG and electricity. Shares of LPG and electricity in rural area will not be as high as the urban levels but increase through the next 20 years as well.

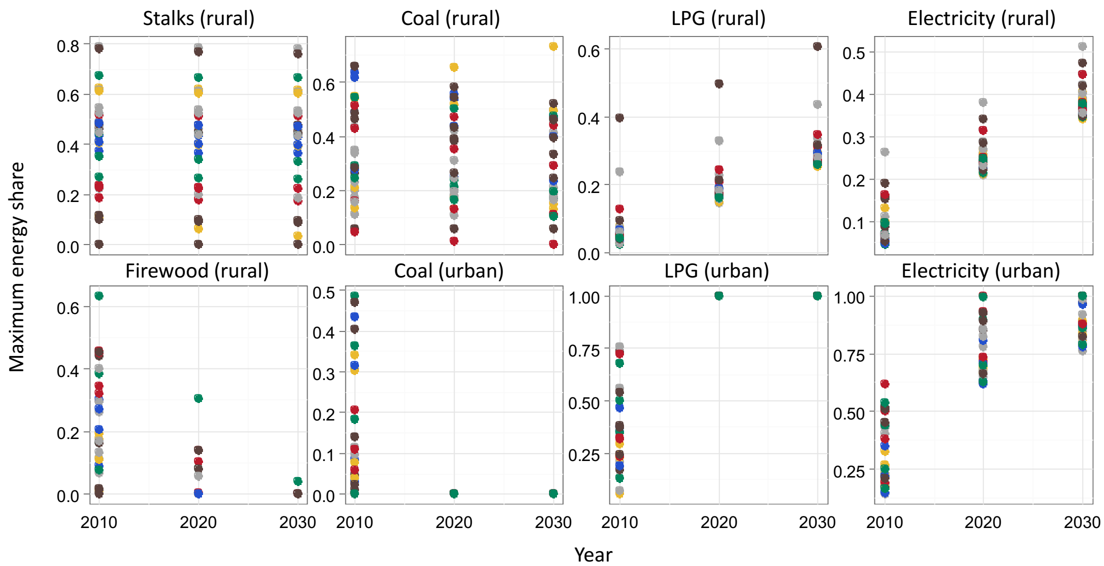

Figure 4. Estimated household energy share

3.2 National energy consumption

Figure 5 shows the estimated energy consumption in China's residential sector. In BaU scenario where energy transition process is not taken into account, there is clearly an overestimation of gas share in urban China, and an underestimation of coal share in rural China. In 2010 gas only shares about 10% of the total energy consumption in urban residential sector. It is unlikely that this share could suddenly reach 70% in a short period as 20 years. Coal is currently a major energy carrier in rural China. In BaU scenario the use of coal in rural households switches to traditional biomass due to its lower cost and emission factor. In ET scenario the emission reduction is moderate but falls in a reasonable range, and coal still ranks as the second major energy source. Furthermore, effected by the constraints of coal and traditional biomass share in rural area, use of commercial (the next generation) biomass is observed in ET scenario

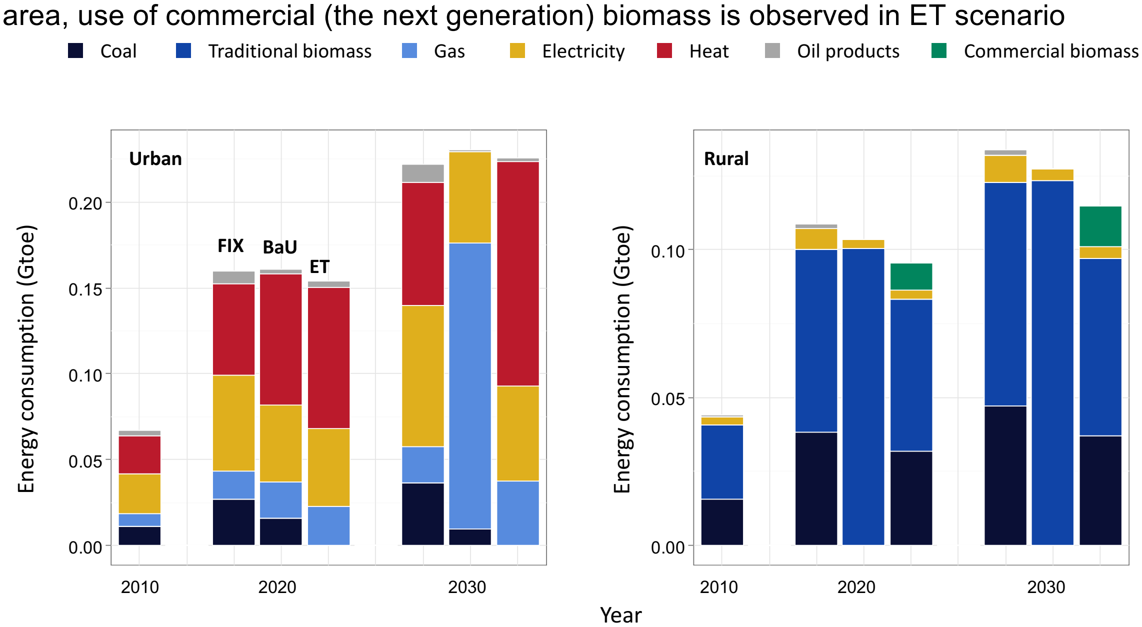

Figure 5. Energy consumption

3.3 CO_2 emission

Figure 6 shows the estimated results of CO_2 emission in urban and rural areas. The cost optimization simulation in AIM/Enduse results the bulk of traditional biomass consumption hence an underestimation of CO_2 emission in BaU. The national results in Figure 6 are aggregated national total of 31 provincial regions. To examine the impact of socioeconomic development on energy transition and carbon emission, we select Beijing and Tibet as two socioeconomic representatives and compare their results. Beijing is the capital city of China with cold climate and relatively higher socioeconomic status. In urban Beijing, coal will be completely phased out by 2030 and household energy choice is gradually switches to electricity. In rural Beijing traditional biomass will be phased out however coal will remain as the primary energy carrier. Tibet is also a coal region and lies in western China. Compared to Beijing, Tibet has lower socioeconomic status which resulted different energy shares. Similar to Beijing's projection, coal will be phased out in urban Tibet. However electricity share will not climb to as high as Beijing's level due to the lower income level in urban Tibet. Also in rural Tibet traditional biomass will not be completed phased out by 2030.

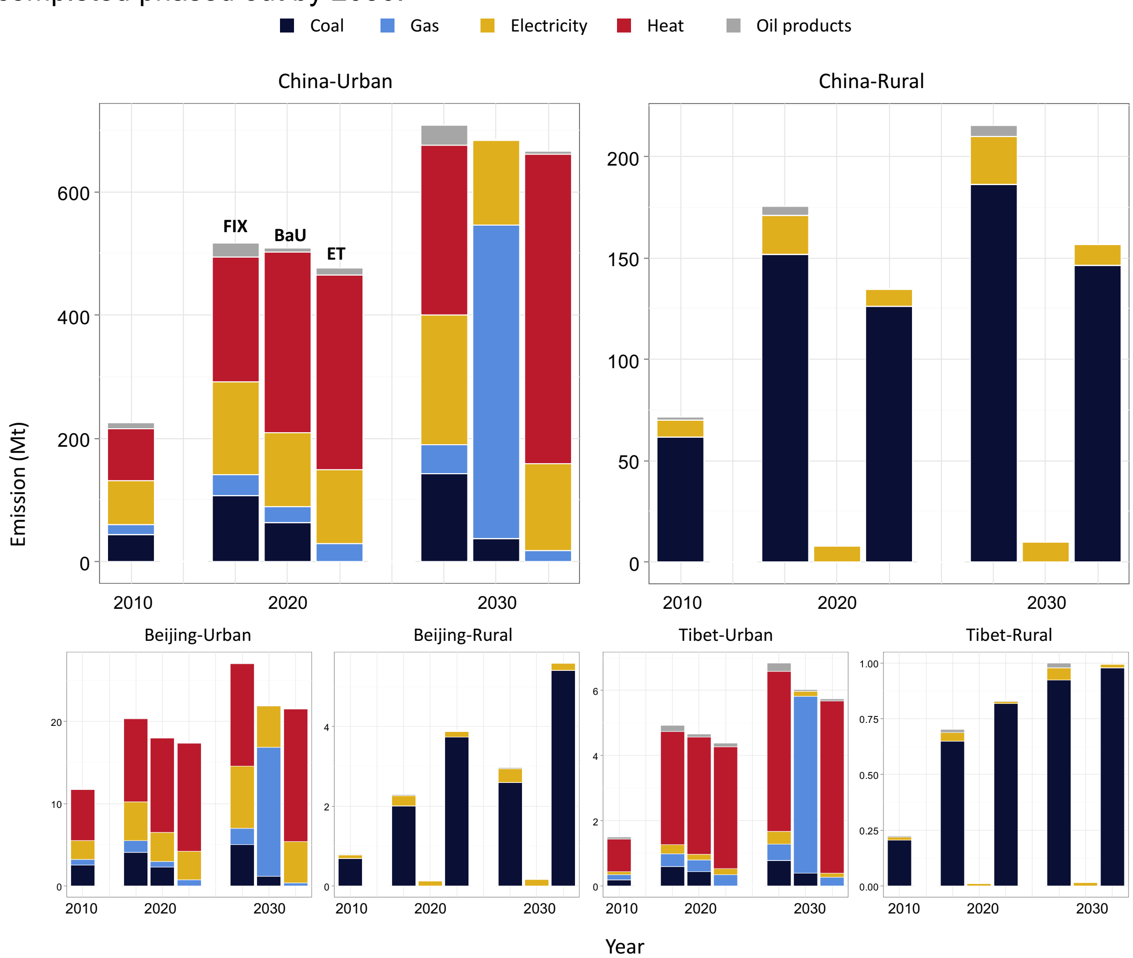

Figure 6. National and regional of CO_2 emissions

3.4 Particulate matter 2.5 ($PM_{2.5}$) emission

Overestimation or underestimation of certain energy use not only effect on CO_2 emission estimations but also some air-pollutants. Besides CO_2 we also evaluate emissions of black carbon, $PM_{2.5}$ and sulfur dioxide in three proposed scenarios, in which $PM_{2.5}$

emission estimation is alternated the most by introducing the energy transition process. Figure 7 shows the estimated $PM_{2.5}$ emission in urban and rural areas. Without consideration of energy transition, $PM_{2.5}$ emission will be overestimated in BaU scenario. Especially in rural area, as discussed in Section 3.3 CO_2 emission can be largely reduced by using the carbon neutral fuel traditional biomass. However, pushing energy transition backwards to tradition biomass will lead to increase of $PM_{2.5}$ emission and therefore bring the risk of non-energy (health) problems.

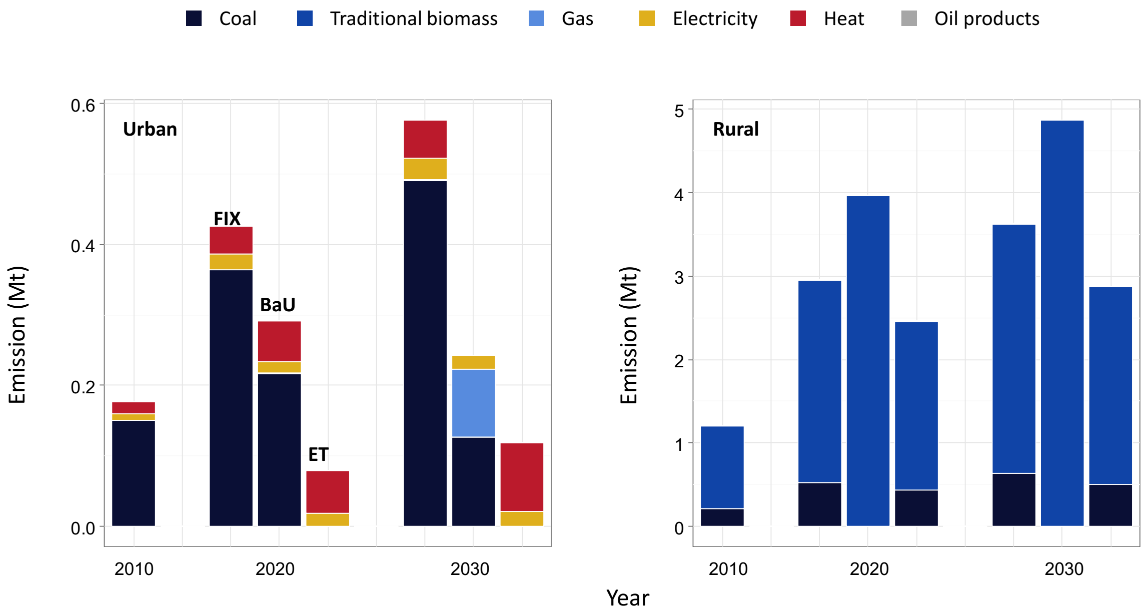

Figure 7. National $PM_{2.5}$ emission

4. Conclusion

In this study we address the relation between socioeconomic development and household energy choice and select 12 socioeconomic indicators to estimate the future household energy share in China. As results from regression analysis, coal is expected to be phased out during the next decade in urban China but still holds a certain share in rural China. Energy consumption and gas emissions are estimated in scenarios with and without consideration of energy transition. The results suggest that without considering energy transition, there is clearly an overestimation of gas share in urban China, and an underestimation of coal share in rural China which furthermore effect the CO_2 emission estimation in the future. Overestimation is also observed in $PM_{2.5}$ emission in BaU (without energy transition) scenario.

Acknowledgements

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