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Residential Energy Consumption and Associated Carbon Emission in Forest Rural Area in China: A Case Study in Weichang County

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Abstract: Rural energy consumption in China has increased dramatically in the last decades, and has become a significant contributor of carbon emissions. Yet there is limited data on energy consumption patterns and their evolution in forest rural areas of China. In order to bridge this gap, we report the findings of field surveys in forest villages in Weichang County as a case study of rural energy consumption in northern China. We found that the residential energy consumption per household is 3313 kgce yr^{-1} (kilogram standard coal equivalent per year), with energy content of 9.7 × 107 kJ yr^{-1}, including 1783 kgce yr^{-1} from coal, 1386 kgce yr^{-1} from fuel wood, 96 kgce yr^{-1} from electricity, and 49 kgce yr^{-1} from LPG. Per capita consumption is 909 kgce yr^{-1} and its energy content is 2.7 × 107 kJ yr^{-1}. Due to a total energy utilization efficiency of 24.6%, all the consumed energy can only supply about 2.4 × 107 kJ yr^{-1} of efficient energy content. Secondly, household energy consumption is partitioned into 2614 kgce yr^{-1} for heating, 616 kgce yr^{-1} for cooking, and 117 kgce yr^{-1} for home appliances. Thirdly, the associated carbon emissions per household are 2556 kgC yr^{-1}, including 1022 kgC yr^{-1} from unutilized fuel wood (90% of the total fuel wood). The rest of emissions come from the use of electricity (212 kgC yr^{-1}), coal (1301 kgC yr^{-1}) and LPG (21 kgC yr^{-1}). Fourthly, local climate, family size and household income have strong influences on rural residential energy consumption. Changes in storage and utilization practices of fuel can lead to the 10%-30% increase in the efficiency of fuel wood use, leading to reduced energy consumption by 924 kgce yr^{-1} per household (27.9% reduction) and 901 kgC yr^{-1} of carbon emissions (35.3% reduction).

Keywords: Energy consumption; Carbon emission; Rural areas; Fuelwood; Utilization efficiency

Introduction

Energy consumption plays the critical role in modern economic development, and currently even more in emerging and developing economies (Zhang et al. 2010; Zheng et al. 2010; Kishore et al. 2004; Islam et al. 2006). As the largest developing country, China's energy demand has accelerated,

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owing to its rapid economic development, especially after the year of 1978. China's primary energy consumption increased from 0.57 billion tons of coal equivalents (btce) in 1978 to 3.25 btce in 2010, with the average annual growth of 5.6%. China's total energy consumption is expected to be 4.7 btce by 2020 (Fan and Xia 2012). However, the low energy utilization efficiency (the ratio of supplied energy content to total energy content of the consumed fuels), has resulted in increased environmental pollution and impacts on human health. Moreover, China is now the single largest carbon emitter in the world, with comparable per capita emissions from those of the European Union, but lower than the U.S.A. (Chen et al. 2006; Zhao et al. 2012; Peters et al. 2012; Le Quere et al. 2013).

Over 1.5 billion people in rural areas have unmet energy needs for cooking, lighting, and heating, with biomass fuels being the primary energy source (GEA 2012; Johnson and Bryden 2012; International Energy Agency 2010). Thereby, continuous rural development has highlighted the need for energy security and environmental protection (Johnson and Bryden 2012; Bond and Sun 2005; Jetter and Kariher 2009; Madubansi and Shackleton 2006; Ramanathan and Carmichael 2008). In 2009, there were more than 700 million people living in rural areas in China alone. In recent years, due to rapid rural development, rural energy consumption has substantially increased in China, from 307.19 mtce (million ton of standard coal equivalent) in 1979 to 977.14 mtce in 2007, with the annual growth of 4.2% (Zhang et al. 2009). Per capita energy consumption showed an even faster growing trend, from 388.78 kgce (kilogram of standard coal equivalent) in 1979 to 1343.14 kgce in 2007 (Zhang et al. 2009). Although rural energy consumption patterns are changing, rural residents still prefer straw, fuel wood and coal as their main energy source, accounting for 90% of the total energy consumption (Zhou et al. 2008; Chen et al. 2012). The low energy utilization efficiency in the way these fuels are utilized, has contributed to the increased need for more raw materials. Associated with this growth in energy demand, carbon dioxide emission from rural residential energy consumption in China grew from 152.22 MtC in 2001 to 283.58 MtC in 2008 (Yao et al. 2012).

In order to achieve sustainable development, Chinese government in 2009 announced a target for reducing carbon intensity of the economy (carbon emissions per GDP) of 40%-45% by 2020, based on 2005 levels (Fan and Xia 2012). Given its rapid growth, there is large interest in exploring the potential for carbon mitigation of rural residential energy consumption (Zhang et al. 2010; Chen et al. 2012; Yao et al. 2012; Wang et al. 2011).

The consumption of rural energy varies from region to region due to their distinct location, economy and climate (Zhou et al. 2008; Zhou et al. 2009; Li et al. 2009; Nautiyal 2013). Fuel wood is one of the key energy sources in forest rural areas thanks to abundant biomass production from forest operations (Cai and Jiang 2010). Increasing demand has often resulted in over-extraction of wood often leading to deforestation and forest degradation, with loss of soil fertility and increased risk of floods and sand-storms (Cai and Jiang 2010; Liu 2005). Conversely, sustainably managed forests can lead to increased biomass production, while preserving other valuable ecosystem services of regional and global importance, like carbon sequestration. Despite its importance, there is limited quantification of rural energy consumption patterns and its associated carbon emission in China (Cai and Jiang 2010).

The objective of this paper is to assess the residential energy consumption and its associated carbon emissions in forest rural communities of China. We achieved this objective as a case study of northern China through extensive field surveys in Weichang County, focusing on the residential energy needs for cooking, heating, home appliances, and other needs. In addition, we analyzed the environmental and economic factors that influence rural residential energy consumption and its carbon emissions. Finally, we assess the carbon mitigation potential by improving fuel wood utilization efficiency.

1 Material and Methods

1.1 Study area

We conducted our surveys in Weichang County located in the Hebei Province (41°35'–42°40'N, 116°32'–118°14'E), a typical area in the north of China. Winters are cold and dry with an average temperature of -1.4°C–4.7°C, and -13.2°C for January; average temperature for July is 20.7°C. Household heating is needed during the cold period (November to April), but it is not required during the rest of the year. Annual rainfall is about 445 mm, mainly in summer. Weichang County has a high forest cover and abundant forest biomass resources in the way of forest plantations. In 2011, about 37,633 m^3 of biomass were harvested for wood products and fuel wood. Weichang County has 267,000 people living in forest rural areas, about 52% of the total population. We selected three typical forest villages as our study area, Village no. 27 in Dahuanqi Town, Qipanshan Village in Qipanshan Town, and Shizhuozi Village in Shizhuozi Town. All the three villages are near to the Mulan Weichang Stated-owned Forest, with most of the local residents making their living on agriculture or forestry land.

1.2 Field surveys

We conducted face-face structured interviews from July to August 2012 and investigated 79 households, including 30 households in Village No.27, 30 households in Qipanshan Village, and 19 households in Shizhuozi Village. We surveyed the basic household information including family size, family annual income, and number of rooms (Table 1).

Table 1 Basic household information in our study area (mean ± standard deviation)

Family size	Family annual income[a]	House rooms
4.05±1.49	2.17±0.87	4.09±1.37

Note: [a]We divided the family annual income into four categories. Annual income less than 10,000 Yuan, we recorded as “1”; if the annual income was between 10, 000 and 30,000 Yuan, we recorded as “2”; if the annual income was between 30,000 and 50,000Yuan, we recorded as “3”; if the annual income was more than 50,000 Yuan, we recorded as “4”.

For residential energy consumption, our surveys focused on (a) the main energy sources; (b) the magnitude of different energy consumption per year or per month; (c) the end use of different energy resources (heating, cooking and home appliances); (d) the duration of use of different energy sources; and (e) the utilization efficiency of different energy resources (the ratio of supplied energy to the total energy content of the consumed fuel).

There are very few private cars and machines in the study area, with little oil being consumed. Thus, our research focuses on residential energy sources including fuel wood, electricity, coal, and bottled liquefied petroleum gas (LPG), which were mainly used for cooking, heating and home appliances (including lighting, entertainment, and others).

1.3 Calculations

We calculated the total energy consumption (unit: standard coal equivalent (ce)) and its energy content (kJ), the supplied energy content (kJ). In addition, we also estimated carbon emission from residential energy consumption. The detailed information is as follows:

1.3.1 Rural residential energy consumption

We estimated the consumption of all energy sources, and converted them to standard coal equivalent (ce), using the conversion coefficients in Table 2. We also estimated their energy content, with the unit of kJ, and then summarized them to the total energy content of all the fuel wood, electricity, coal, and LPG. As some fuels cannot be fully converted into usable energy, thus, we here also estimated the supplied energy content of different energy fuels.

Table 2 Energy source conversion coefficients to standard coal (Cai and Jiang 2010)

Energy source	Conversion coefficients to standard coal		
	Unit	10^7 J	kg of standard coal equivalent
Fuel wood	kg	1.8	0.61
Electricity	kWh	0.36	0.12
Coal	kg	2.93	1.00
LPG	One bottle(15 kg)	75	25.60

Taking the utilization efficiency into account, energy fuels cannot provide all the energy stored in them. Thus, based on our surveys and previous studies, we summarized their utilization efficiency as follows: Fuel wood, 10%; Coal, 30%; Electricity, 100%; and LPG 100% (Wang et al. 2006; Zhou et al. 2008)

1.3.2 Carbon emission from residential energy consumption

Fuel wood is often considered carbon neutral, particularly if they are sourced from local forestry residues, as regrowth or replanting will take up atmospheric carbon dioxide. Electricity, coal, and LPG are net emitters. We calculated carbon emission from rural residential energy (excluding fuel wood) as equation 1.

$$C_{t-f} = \sum_i \delta_i E_i \quad (1)$$

Where, $C_{t\text{-}f}$ is the total carbon emission without fuel wood, δ_i refers to carbon emission coefficients of electricity, coal, and LPG; E_i refers to the consumption of electricity, coal, and LPG. According to previous studies in China (Hu et al. 2008; Xu et al. 2006; CAS Sustainable Development Strategy Study Group 2009), the coefficients of carbon emissions from electricity, coal, and LPG are 2.21, 0.73, and 0.42 kgC kgce^{-1}, respectively.

Some fuel wood is wasted without providing any energy or heat, but will release carbon to atmosphere. Thus, we also estimate carbon emission from the unutilized part as follows:

$$C_{wnf} = 0.5 \times (1-\eta_w) \times M_w \quad (2)$$

where, C_{wnf} denotes carbon emission from the unutilized fuel wood; 0.5 is the carbon ratio, which means 50% of dry biomass is carbon; η_w is the fuel wood utilization efficiency; and M_w is the actual fuel wood consumption, unit of kg.

Thus, taking carbon emission from the unused fuel wood into account, the total carbon emission from residential energy consumption is:

$$C_t = C_{t-f} + C_{wnf} \quad (3)$$

where, C_t denotes total carbon emission with the unutilized fuel wood.

2 Results

2.1 Survey Results

Fuel wood, electricity, coal and LPG are the main residential energy sources in forest rural areas in north of China, and they are mainly consumed for cooking, heating and home appliances. Table 3 summarizes our survey results, including end use, utilization duration, and energy allocation proportion. The detailed results are as follows:

Fuel wood. Fuel wood is mainly consumed during the cold period (November to next April, six months), and it is used for cooking and heating, accounting for 40% and 60% of the fuel wood consumption, respectively.

Table 3 The utilization purposes, allocation proportion, duration and efficiency of different residential energy sources: fuel wood, electricity (elec.), coal, liquefied petroleum gas (LPG).

Purposes	Energy	Proportion	Duration
Cooking	fuel	40%	6 months Nov-next Apr
	elec.	~ 18 kWh per month	6 months May - Oct
	LPG	100%	whole year
Heating	fuel	60%	6 months Nov-next Apr
	coal	100%	6 months Nov-next Apr
Home appliances	elec.	the rest	whole year

Coal. Like Fuel wood, Coal is also consumed during the cold period, about six months, but it is only used for heating.

Electricity. Electricity consumption is different between cold months and warm months. For the cold period (November to next April, six months), the local inhabitants only consumed electricity for their home appliances. However, during the warm period from May to October, part of electricity (about 18 kWh per month) is used to cook, instead of fuel wood for cooking in winter, and the rest is also used for home appliances.

LPG. All of LPG is consumed for cooking throughout the year.

2.2 Rural residential energy consumption

All households consume electricity, and fuel wood and coal provide the highest share of the total energy. Although the LPG share is relatively low, there are still 64 out of 79 households consuming LPG for cooking (Table 4). Table 4 illustrates the annual magnitude of residential energy consumption in the study area.

The total consumption of rural residential energy per household is 3313 kgce yr^{-1}, with the energy content of 9.7×10^{7} kJ yr^{-1}, while the per capita consumption is 909 kgce yr^{-1} and its energy content is 2.7×10^{7} kJ yr^{-1}. Coal consumption per household is largest at about 1782 kgce yr^{-1}, followed by 1386 kgce yr^{-1} of fuel wood, and they account for 50.3% and 45.1% of the total rural

Table 4 The annual magnitude of residential energy consumption in our study area

Energy sources	HU	Per household Consumption (kgce yr⁻¹)	Per household EC (kJ yr⁻¹)	Per capita Consumption (kgce yr⁻¹)	Per capita EC (kJ yr⁻¹)	Proportion	Per room Consumption (kgce yr⁻¹)	Per room EC (kJ yr⁻¹)
Fuel wood	75	1386±799	4.1±2.3	429±451	1.3±1.3	45.1%	377±249	1.1±0.7
Electricity	79	96±56	0.3±0.2	26±15	0.1±0.0	3.1%	-	-
Coal	73	1782±1315	5.2±3.8	442±432	1.3±1.3	50.3%	427±410	1.3±1.2
LPG	64	49±43	0.1±0.1	12±10	0.03±0.02	1.5%	-	-
Total energy	-	3313±1435	9.7±4.2	909±522	2.7±1.5	-	-	-
Efficient energy	-	-	2.4±1.3	213±99	0.6±0.3	-	-	-

Notes: HU = The number of households utilizing this type of energy; EC = Energy content.

residential energy consumption, respectively. Besides, the energy contents of consumed coal and fuel wood are 5.2×10^7 kJ yr^{-1} and 4.1×10^7 kJ yr^{-1}. The consumption of electricity per household is about 96 kgce yr^{-1}, contributing to the energy content of 0.3×10^7 kJ yr^{-1}, while the consumption and energy content of LPG per household is 49 kgce yr^{-1} and 0.1×10^7 kJ yr^{-1}. However, due to the low utilization efficiency of coal and fuel wood, the energy content stored in them can't be fully released. Thus, all the consumed energy fuels can only provide 0.3×10^7 kJ yr^{-1} of energy content, corresponding to 818 kg of standard coal equivalent, while the utilization efficiency of the rural residential energy is only about 24.7%.

Although the consumption of electricity and LPG is very low, about of 3.1% and 1.5% of all the consumed energy, the proportion of energy content provided by electricity and LPG amount to 11.7% and 6.0% respectively, thanks to their high utilization efficiency. Furthermore, the consumption of fuel wood and coal per room are about 377 kgce yr^{-1} and 427 kgce yr^{-1}, with the energy content of 1.1×10^7 kJ yr^{-1} and 1.3×10^7 kJ yr^{-1}.

Table 5 shows the end use patterns of residential energy fuels in our study area. Due to cold winters, most of the residential energy sources are consumed for heating, 2614 kgce yr^{-1} per household or 77.3% of total energy consumption, with the energy content of 7.7×10^7 kJ yr^{-1}. Per capita energy consumption for heating is 699 kgce yr^{-1} and about 657 kgce yr^{-1} is consumed per room, their energy contents being 2.0×10^7 kJ yr^{-1} and 1.9×10^7 kJ yr^{-1}. Taking utilization efficiency into account, the consumed energy for heating supplies only 1.9×10^7 kJ yr^{-1} of energy content, and its utilization efficiency is only 23.6%. Apart from heating, each household also consumes about 616 kgce yr^{-1} energy for cooking (the energy content of 1.8×10^7 kJ yr^{-1}), while its energy content is only 0.3×10^7 kJ yr^{-1}, with the utilization efficiency of 19.0%. Home appliances only consume 2.7% of the total rural residential energy in our study area, but its efficient energy content amounts to 10.9% of the total energy content supplied from all the consumed energy fuels, owing to its high utilization efficiency.

We find that there is a constant consumption of LPG throughout the year, at about 4 kgce per month, with energy content of 1.2×10^5 kJ. Thus, we only focus the monthly consumption of the other three energy fuels: fuel wood, electricity and coal (Figure 1). Due to North China's cold winters, more energy fuels are consumed for heating between November and April, and likewise it is when all fuel wood and coal are consumed. Consequently, during that period, the consumption of fuel wood and coal per household are 231 and 297 kgce per month, while only about 7 kgce of electricity is consumed each month per household. Thus, the energy

Table 5 The residential energy consumption pattern in forest rural area

Purpose		Cooking	Heating	Home appliances
Consumption (kgce yr⁻¹)	Mean	616±312	2614±1308	83±56
	Proportion	20.00%	77.30%	2.70%
	Per capita	188±180	699±375	22±15
	Per room	-	657±318	-
Total energy content (kJ yr⁻¹)	Mean	1.4±0.7	6.0±3.0	0.2±0.1
	Per capita	0.4±0.4	1.6±0.9	0.05±0.03
	Per room	-	1.5±0.7	-
Supplied energy (kJ yr⁻¹)	Mean	0.3±0.1	1.4±0.9	0.2±0.1
	Proportion	17.00%	72.00%	10.90%
	Per capita	0.1±0.05	0.4±0.2	0.05±0.03
	Per room	-	0.3±0.2	-

contents of consumed fuel wood is 0.7×10^7 kJ, while their energy content of consumed coal and electricity are 0.9×10^7 kJ, and 2.1×10^5 kJ, respectively. About 539 kgce per month of residential energy, with the energy content of 1.5×10^7 kJ per month, is consumed during the cold period. There is no fuel wood and coal consumption, but electricity consumption increased to 9 kgce during the warm period (May to September), with the energy content of 2.6×10^5 kJ. As well as the consumption of LPG at 4 kgce per month, the total residential energy consumption is 13 kgce per month during warm months, and its energy content amounts to 3.8×10^5 kJ per month. This is because more electricity is consumed for cooking, instead of part of fuel wood consumed for cooking during the cold period. Since electricity and LPG is assumed to be fully utilized in warm months, energy content supplied by energy fuels is also 3.0×10^5 kJ per month then, equivalent to the energy content stored in 13 kg standard coal. For the cold months, coal, fuel wood, electricity, and LPG supply the energy content of 2.6×10^6, 6.7×10^5, 2.0×10^5 and 9.2×10^4 kJ per month, summarizing up to the total energy content of 3.5×10^6 kJ per month.

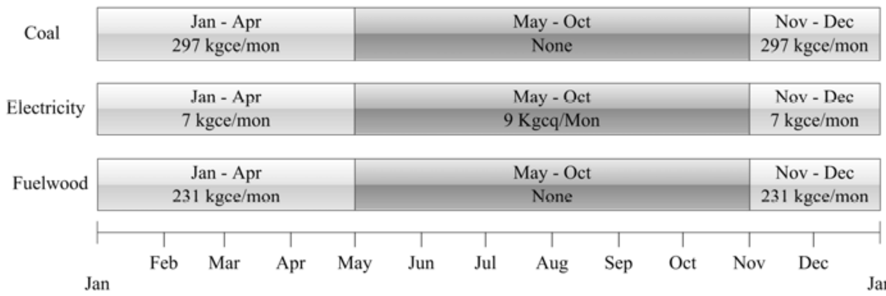


Figure 1 Monthly residential consumption of fuel wood, electricity and coal in study area.

2.3 Carbon emission from rural residential energy consumption

The annual household carbon emissions are 212 kgC yr^{-1} from electricity, 1301 kgC yr^{-1} from coal and 21 kgC yr^{-1} from LPG (see Table 6). Thus, without carbon emission from fuel wood, the total carbon emission from residential energy consumption per household amounts to 1534 kgC yr^{-1}. Fuel wood is considered as "carbon neutral" energy, if all of them fully utilized. However, some fuel wood is wasted, which cannot be used for supplying energy, and thus this part of fuel wood is accounted for carbon emission here. Carbon emission from the unutilized fuel wood is about 1022 kgC yr^{-1} per household, and thus the total emission (with fuel wood) accounts for up to 2556 kgC yr^{-1}. With carbon emission from fuel wood, the per capita carbon emissions are 701 kgC yr^{-1}. There were great differences of carbon emission among households, with the maximum of 6128 kgC yr^{-1} and the minimum of 57 kgC yr^{-1}. More importantly, carbon emission intensity of total energy content (the ratio of total carbon emissions to the total consumed energy content), is about 0.026 gC kJ^{-1} in our study area, but the carbon intensity of efficient energy content (the ratio of total carbon emissions to the total supplied energy content) amounts to 0.106 gC kJ^{-1}.

Table 7 shows the annual household carbon emissions from residential energy consumption for different purposes of end use. Similar to the pattern of residential energy consumption, carbon emission from heating is the highest, followed by cooking and home appliances. More precisely,

Table 6 Annual carbon emission from rural residential energy consumption (Unit: kgC yr^{-1})

Carbon emission		Fuel wood	Electricity	Coal	LPG	Total emission	
						Without fuel wood	With fuel wood
Household	Mean	1022±589	212±124	1301±960	21±18	1534±1037	2556±1082
	Maximum	3375	810	5840	129	6128.00	7270
	Minimum	0	57	0	0	57.00	914
Ration	Without fuel wood	-	21.0%	77.3%	1.7%	-	-
	With fuel wood	43.0%	8.8%	47.3%	0.8%	-	-
Per person		317±332	57±33	322±194	5.1±4.0	384±211	701±390
Per room		278±183	-	312±216	-	370±235	652±283

heating plays the vital role in carbon emissions of residential energy consumption in our study area, at about 1915 kgC yr^{-1} per household, accounting for 73.1% of total carbon emissions. Following heating, annual carbon emission from cooking amounts to 458 kgC yr^{-1}, while the least carbon emission is from home appliances at only 184 kgC yr^{-1}. Per capita carbon emissions from cooking is about 140 kgC yr^{-1}, with 513 kgC yr^{-1} from heating and 48 kgC yr^{-1} from home appliances. For heating, each room emits an average of about 481 kgC yr^{-1} of carbon. For home appliances, its carbon intensity of total energy content is 0.075 gC kJ^{-1}, further higher than 0.026 gC kJ^{-1} for cooking and 0.025 gC kJ^{-1} for heating. However, taking the efficiency into account, the carbon intensity of efficient energy content for home appliances is much lower than that of the other end use, and the carbon intensity of efficient energy content for cooking and heating soar up to 0.133 gC kJ^{-1} and 0.106 gC kJ^{-1}, respectively.

Table 7 **Annual carbon emission from rural residential energy consumption for different end uses**

Carbon emission			Cooking	Heating	Home appliances
Consumption (kgce yr^{-1})	Household	Mean	458±232	1915±955	184±124
		Maximum	1379	5920	781
		Minimum	39	473	29
	Ration		19.30%	73.10%	7.5%±4.2%
	Per person		140±136	513±275	48±32
	Per room		-	481±232	-
Total energy content (gC kJ^{-1})			0.026	0.025	0.075
Supplied energy content (gC kJ^{-1})			0.133	0.106	0.075

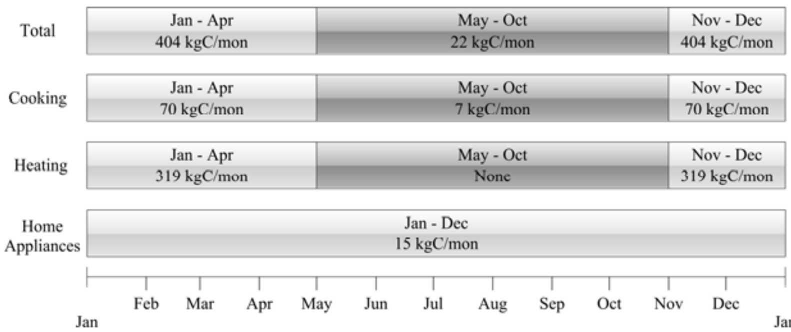


Figure 2 Household monthly carbon emission from energy consumption for different purposes.

Figure 2 presents household monthly carbon emissions from rural residential energy consumption. Similar to monthly energy consumption, the whole year can be divided into two parts: the cold and warm periods. During the cold period, monthly carbon emissions are very high at about 404 kgC per month per household, and 78.9% of which is from heating (319 kgC per month). Each household release about 70 kgC per month for cooking during the cold period, and carbon emission from home appliances is the smallest, only accounting for 3.8% of total carbon emissions then. However, for the warm period, home appliances emit the largest carbon emission at about 15 out of 22 kgC per month, and the remainder of carbon emission is from cooking, accounting for 30% (or 7 kgC per month).

Figure 3 compares the composition of carbon emissions during the cold and warm periods. During the cold period, the maximum carbon emission is from coal combustion (about 216 kgC per month), followed by fuel wood, and they account for 54% and 42% of the total carbon emissions, respectively. Household carbon emission from electricity increases about 5 kgC per month, from 15 kgC per month in the cold period to 20 kgC per month in the warm period. Furthermore, the proportion of carbon emission from electricity is 92% during the warm period. The carbon emission from LPG is constant at about 2 kgC per month all over the year.

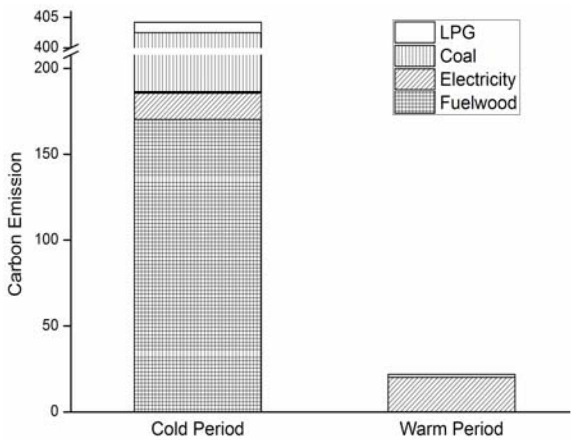


Figure 3 Carbon emission compositions from residential energy consumption for different periods.

3 Discussion

3.1 Factors affecting residential energy consumption and associated carbon emission

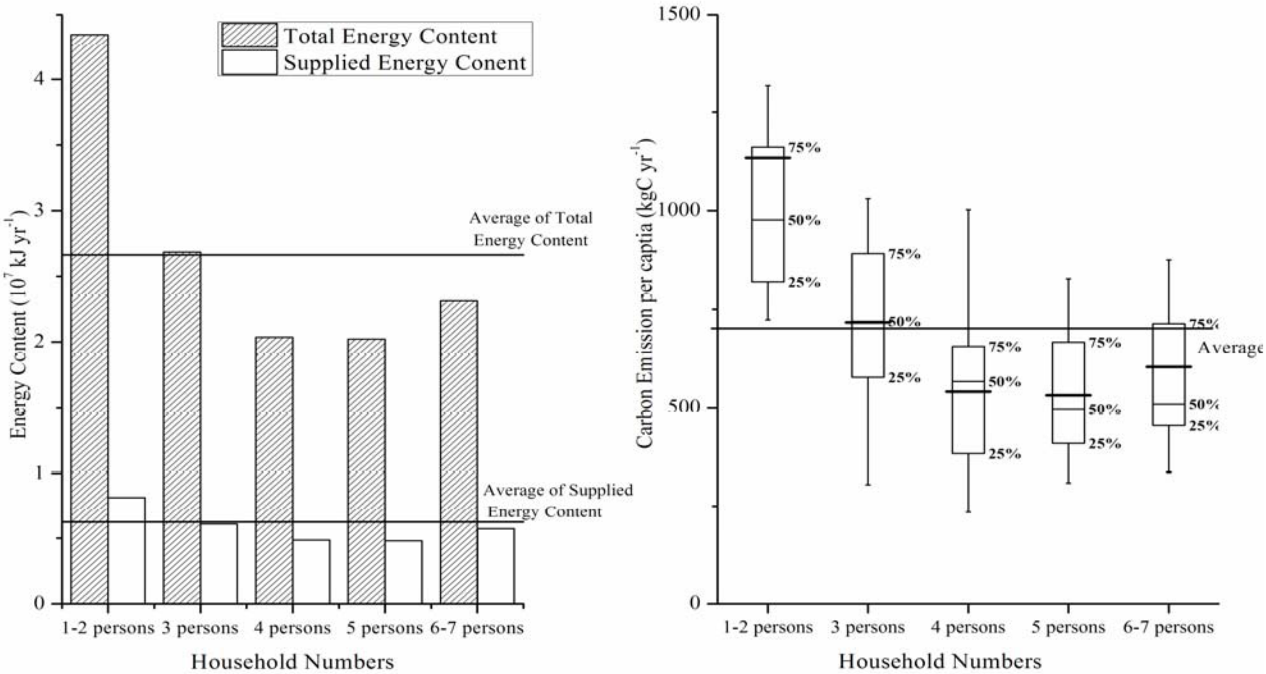
Local climate has a strong influence on residential energy consumption and its associated carbon emission there, largely influenced by the need for more energy during cold periods to warm households. In addition, family size and income are also important factors to determine energy consumption.

3.1.1 Family size

Figure 4 shows the correlation between family size and residential energy consumption (4a) and carbon emission (4b) from energy consumption. For the smallest family size (1~2 persons a house), per capita residential energy consumption is 1483 kgce yr^{-1}. The total energy content is 4.3×10^7 kJ yr^{-1} but only supplying 0.8×10^7 kJ yr^{-1} of sufficient energy content, corresponding to the energy content stored in 279 kg standard coal. The per capita carbon emission from residential energy consumption is 1134 kgC yr^{-1} for the family size of 1~2 persons per household. Both of per capita energy consumption and its associated carbon emission show a decreasing trend with family size, but the per capita energy consumption is still larger than the average 3-person family. The decreasing trend is mainly because some components of energy consumption are constant and does not increase with family size. For other families, the per capita energy consumption and carbon emissions are both lower than their national levels. For 4-person and 5-person households, per capita energy consumption and associated carbon emissions are similar, at about 690 kgce yr^{-1} and 535 kgC yr^{-1}, respectively. However, the largest households (6~7 persons per house) had greater per capita energy consumption than 5-person families.

3.1.2 Family income

The annual family income is about 30,000~50,000 Yuan in the study region, and Table 8 shows that the household annual residential energy consumption and associated carbon emission grow with the increase of family income. More specifically, the total energy consumption is 2730 kgce yr^{-1} (about 8.0×10^7 kJ yr^{-1} of energy content) for the lowest income families (level 1), while it amounts to 4332 kgce yr^{-1} of energy consumption and 12.7×10^7 kJ yr^{-1} of energy content for the family income level of 5 (the



a Total and Supplied Energy Content per Capita

b Carbon Emission per Capita

Figure 4 The relationship between family size and energy consumption/carbon emission.

Table 8 The relationship between family income and energy consumption/carbon emission				
Income Level	1	2	3	4
Household	16	41	14	8
Total energy consumption (kgce yr^{-1})	2730±1057	3064±1115	4129±1742	4332±1793
Total energy content (kJ yr^{-1})	8.0±3.1	9.0±3.3	12.1±5.1	12.7±5.3
Supplied energy content (kgce yr^{-1})	1.5±0.6	2.1±0.8	3.1±1.5	3.3±1.7
Energy use efficiency	18.4%	23.4%	25.2%	25.9%
Carbon emission (kgC yr^{-1})	2084±787	2372±827	3188±1363	3343±1279
Carbon emission of total energy content (gC kJ^{-1})	0.026	0.026	0.026	0.026
Carbon emission of supplied energy content (gC kJ^{-1})	0.142	0.113	0.104	0.101

highest income). Energy supplied energy is 1.5×10^7 and 3.3×10^7 kJ yr^{-1} for level 1 and 5, respectively. The energy utilization efficiency also increases slightly, from 18% to 26%. For carbon emission, the highest income families emit about 1259 kgC yr^{-1} more carbon per household than that from the lowest income households, about 2084 and 3343 kgC yr^{-1}, respectively. Although high-income families lead to much more carbon emissions, all families have the same carbon intensity of total energy content, about 0.026 gC kJ^{-1}. However, the carbon intensity of efficient energy content is different, with a decreasing trend with income increase. It is about 0.142 gC kJ^{-1} for the lowest income level families, compared with 0.101 gC kJ^{-1} for the highest income level families. The difference is mainly because high income families prefer LPG and electricity to other cheaper energy sources, like fuel wood and coal. Although LPG and electricity are more expensive, their carbon intensity is much lower and their utilization efficiency is much higher. Thus, carbon intensity of efficient energy content in high income families is much lower than that in low income families.

3.2 Comparison with other rural areas

We compare our results with other available studies summarized in Table 9.

(1) Forest rural energy consumption in South China and North China

In South China, the total residential energy consumption per household is 2446 kgce yr^{-1} in forest villages, near Longxi-Hongkou Forest Nature Reserve (Cai and Jiang 2010); this is lower than our results of 3313 kgce yr^{-1} in forest villages in north of China. From energy fuels composition, we can find that the main difference is from coal consumption. Each household consume 739 kgce yr^{-1} more coal in north of China than that in south of China. North China has long cold winters, and thus local rural households consume more coal in order to keep warm. However, the consumption of fuel wood, electricity and LPG is similar in the south and north of China. We also find that fuel wood and coal are the main residential energy fuels in forest rural areas all over China, and the consumption of other energy fuels is relatively low. The main reason is that there is abundant forest biomass as energy fuels in forest villages. Besides, the energy consumption patterns are also high related to their long-term living habits and local customs, because of the local rich biomass energy.

(2) Energy consumption in forest and non-forest rural areas in Northeast China

As the coldest region in China (Zhou et al. 2008), heating is vital during the cold winter in Northeast China, and thus energy for heating is the main end use of energy consumption. Biomass energy is abundant thanks to local fertile soil, and thus biomass is the dominant energy source in Northeast China. The total residential energy consumption is 506.37 kgce yr^{-1} (Zhou et al. 2008) in the rural areas of Northeast China, with the energy content of 1.5×10^7 kJ yr^{-1}, which is slightly higher than the supplied energy content of 1.3×10^7 kJ yr^{-1} in our study area. In other rural area in Northeast China, the biomass consumption consisted of 376.31 kgce yr^{-1} straw and 130.06 kgce yr^{-1} fuel wood. However, the fuel wood consumption in these rural areas only amounts to 30% of fuel wood consumption in our study area. Thus, we can conclude that fuel wood plays an important role in energy consumption in forest rural areas. The efficiency of coal consumption (442kgce yr^{-1}) is higher in our study area than the

Table 9 Comparison of the rural residential energy consumption and its associated carbon emission with the previous reports in China

With rural forest areas	Comparison	Longxi-Hongkou (Cai and Jiang 2010)	This research
	Location and climate	South China, with humid monsoon subtropical climate, and average annual temperature being 15.2°C	North China, with cold and dry winter and annual average temperature being about -1.4°C—4.7°C
	Energy consumption	Annual energy consumption was about 2446 kgce with 1242 kgce fuel wood, 1043 kgce coal, 85 kgce electricity, and 76 kgce LPG	Annual energy consumption is about 3313 kgce with 1386 kgce fuel wood, 1782 kgce coal, 96 kgce electricity, and 49 kgce LPG
With North China	Comparison	Northeast China (Zhou et al. 2008)	This research
	Per capita energy consumption in the rural area	In 2005, total per capita energy consumption was 799.76 kgce, including straw 376.31 kgce, fire wood 130.06 kgce, coal 215.99 kgce, electricity 49.40 kgce, others 28 kgce	Total per capita energy consumption is 909 kgce, including fuel wood 430 kgce, coal 442 kgce, electricity 26 kgce, LPG 12 kgce
With carbon emission in China	Comparison	The whole China (Yao et al. 2012)	This research
	Per capita carbon emission, and its composition	In 2008, per capita rural carbon emission from commercial energy consumption was 390 kg, and the proportion of coal, electricity, oil, and LPG was 44.49%, 46.97%, 4.51%, and 3.81%, respectively.	Per capita rural carbon emission from energy is 384 kgC without fuel wood, including 322 kgC from coal, 57 kgC from electricity, 5.1 kgC from LPG. Besides, fuel wood also emitted 317 kgC.

average coal consumption, about 215.99 kgce yr^{-1}, while the consumption of other energy sources shows little difference. Thereby, total household energy consumption in our study area is slightly higher than the average energy consumption in Northeast China.

(3) National carbon emission from rural residential energy consumption

In rural areas of China, per capita carbon emission from energy consumption is 390 kgC yr^{-1} in 2008 (Yao et al. 2012), which is near our research (384 kgC yr^{-1} of carbon without fuel wood). However, carbon emission patterns are different. For the national level, the fractions of carbon emission are 44% from coal, 47% from electricity, 4.5% from oil and 3.4% from LPG. However, in our study area, carbon emissions are mainly from coal consumption, which accounts for 83.9% of the total carbon emission without fuel wood. Per capita carbon emission from electricity is only about 57 kgC yr^{-1} in our research area, accounting for only 14.8%. Since fuel wood cannot be completely utilized, per capita carbon emission from the unutilized fuel wood is about 317 kgC yr^{-1} in our study area, which is almost as large as the carbon emission from coal consumption. In summary, per capita carbon emissions from rural residential energy in our study are 701 kgC yr^{-1}, which is near two fold that of the national average. Furthermore, household carbon emission from residential energy consumption amounts to 2556 kgC yr^{-1} in our study area.

3.3 Efficiency, rural residential energy consumption, and its associated carbon emission

Energy utilization efficiency has a great influence on rural residential energy consumption and its associated carbon emission. Our study shows that each household consumes about 3313 kgce yr^{-1} of energy, with a total energy content of 9.7×10^7 kJ yr^{-1}. However, all the energy only provides about 2.4×10^7 kJ yr^{-1} of the energy content, corresponding to the energy content stored in 818 kg standard coal. Thus, the total energy utilization efficiency is only about 24.7%.

We find that both coal and fuel wood can be used for heating and cooking, and thus they can replace each other. Thus, improving fuel wood utilization efficiency can effectively reduce coal consumption. In our study area, people harvest fuel wood once a year, and fuel wood is stored outdoors where it gets wet and a fraction of it decomposes before being consumed. Wetness also contributes to incomplete combustion in stoves, adding to further inefficiencies. The simple change of practice to storing fuel wood in a drier place or indoors, would significantly increase the efficiency of fuel wood. Thus, we suppose that the fuel wood utilization efficiency would increase from 10% to 30%, and then we calculated the mitigation of the total residential energy consumption and its associated carbon emission. The mitigation amount of coal consumption can be estimated by:

$$E_{cr} = \frac{\delta_w' E_w - \delta_w E_w}{\delta_c} \quad (4)$$

where, E_{cru} refers to the mitigation amount of coal consumption; δ_w , δ_c, δ_w' represents the previous fuel wood efficiency (10%), coal efficiency (30%), respectively, and the improved fuel wood efficiency (30%).

The magnitudes of carbon mitigation from reduced coal consumption and unutilized fuel wood can be calculated as follows:

$$C_{cr-c} = \delta_c E_{cr} \quad (5)$$

$$C_{cr-wnf} = C_{wnf} - C_{wnf}' = 0.5 \times (1-\eta_w) \times M_w - 0.5 \times (1-\eta_w') \times M_w \quad (6)$$

where, C_{cr-c} *and* C_{cr-wnf} refer to the amount of carbon emission mitigation from reduced coal consumption and unutilized fuel wood, respectively; C_{wnf}' denotes carbon emission from the unutilized fuel wood with the improved fuel wood efficiency.

Table 10 shows the mitigation amounts of energy consumption and carbon emission with different fuel wood utilization efficiencies which can be easily attainable with changes in the way fuel wood is utilized in the households. About 924 kgce yr^{-1} of residential energy is reduced per household, with the energy content of 2.7×10^7 kJ yr^{-1}, accounting for 27.9% of the previous total energy consumption, and all of them are from coal consumption. Associated annual household carbon emission decline even more significantly from 2556 kgC yr^{-1} to 1655 kgC yr^{-1}. Of the savings, 674 kgC yr^{-1} is from less coal consumption, and 227 kgC yr^{-1} due to less unutilized fuel wood.

Thereby, in forest rural areas, it is very important to make full use of local abundant biomass resources, like fuel wood, under the basis of sustainable ecosystem management. According to our results, to improve fuel wood utilization efficiency can effectively reduce the dependence on outside energy, like coal. Furthermore, higher fuel wood utilization efficiency can also significantly reduce carbon emission and thus mitigate global climate change, which is beneficial for global and local sustainable development. Thus, to improve the utilization efficiency of fuel wood deserves more attention in order to achieve local sustainable energy consumption and carbon reduction target in forest rural areas.

Table 10 The magnitude of energy consumption and associated carbon emission with different fuel wood utilization efficiency

Efficiency	Wood fuel		Electricity		Coal		LPG		Total	
	EC	CE	EC	CE	EC	CE	EC	CE	EC	CE
10%	1386	1022	96	212	1782	1301	49	21	3313	2556
30%	1386	795	96	212	858	627	49	21	2389	1655
Change	-	-227	-	-	-924	-674	-	-	-924	-901

Notes: LPG = bottled liquefied petroleum gas; EC = energy consumption (kgce yr^{-1}); CE = carbon emission (kgC yr^{-1}).

4 Conclusion

We assessed the residential energy consumption in forest rural areas in Weichang County in north of China, and estimated its associated carbon emission. Fuel wood, electricity, coal and LPG are the main residential energy sources, and the total household energy consumption is 3313 kgce yr^{-1}, with the energy content of 9.7×10^7 kJ yr^{-1}, including 1783 kgce yr^{-1} coal, 1386 kgce yr^{-1} fuel wood, 96 kgce yr^{-1} electricity and 49 kgce yr^{-1} LPG. Per capita residential energy consumption was 909 kgce yr^{-1}, and its energy content is 2.7×10^7 kJ yr^{-1}. The residential energy efficiency is only 24.7%, which equates to the provision of only 2.4×10^7 kJ yr^{-1} of energy content at end use. 77% of the residential energy is consumed for heating, 2614 kgce yr^{-1} per household, followed by 616 kgce yr^{-1} for cooking and 117 kgce yr^{-1} for home appliances. During the cold period households consumes 539 kgce per month and during the warm period consumes 13 kgce per month.

The total carbon

emissions from residential energy consumption are about 2556 kgC yr-1 in our study area, including about 1022 kgC yr-1 from the unutilized fuel wood. The annual household carbon emissions from electricity, coal and LPG are 212 kgC yr-1, 1301 kgC yr-1, and 21 kgC yr-1, respectively. More importantly, carbon intensity of total energy content is 0.026 gC kJ-1, while carbon intensity of efficient energy content is 0.106 gC kJ-1. About 73% of carbon is released from heating, about 1915 kgC yr-1 per household, and annual carbon emissions from cooking and home appliances amount to 485kgC yr-1 and 184 kgC yr-1, respectively. During the cold period, monthly carbon emissions are very high at about 404 kgC per month, while they are only 22 kgC per month during the warm months.

We find that climate, family size and household income have significant influences on residential energy consumption and its associated carbon emissions. We also conclude that energy consumption and its associated carbon emissions can be reduced significantly by increasing fuel wood utilization efficiency. With better wood fuel storage and utilization practices improvement, fuel wood utilization efficiency can easily increase from current 10% to the assumed 30%. If so, it can achieve the reduction of 924 kgce yr-1 energy consumption and 901 kgC yr-1 carbon emissions per household, with the reduction proportions of 27.9% and 35.4%.

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