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Key Points:

- This study discussed the CO2 emissions from Tibet cities
- 5.52 million tons of CO2 were emitted in Tibet in 2014, Lhasa contributes over half of them
- Tibet has a lower per capita emission and a higher emission intensity compared the whole China

Supporting Information:

- Supporting Information S1

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Energy consumption and CO_2 emissions in Tibet and its cities in 2014

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Abstract Because of its low level of energy consumption and the small scale of its industrial development, the Tibet Autonomous Region has historically been excluded from China's reported energy statistics, including those regarding CO_2 emissions. In this paper, we estimate Tibet's energy consumption using limited online documents, and we calculate the 2014 energy-related and process-related CO_2 emissions of Tibet and its seven prefecture-level administrative divisions for the first time. Our results show that 5.52 million tons of CO_2 were emitted in Tibet in 2014; 33% of these emissions are associated with cement production. Tibet's emissions per capita amounted to 1.74 tons in 2014, which is substantially lower than the national average, although Tibet's emission intensity is relatively high at 0.60 tons per thousand yuan in 2014. Among Tibet's seven prefecture-level administrative divisions, Lhasa City and Shannan Region are the two largest CO_2 contributors and have the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 due to their farming/pasturing-dominated economies. This quantitative measure of Tibet's regional CO_2 emissions provides solid data support for Tibet's actions on climate change and emission reductions.

1. Introduction

The Tibet Autonomous Region is one of China's 34 provincial-level divisions. It is located in the most south-westerly part of China and is China's second largest province. Tibet is a vast territory with a sparse population. Its administrative area is 1.2 million km^2 and accounts for one-eighth of the country's geographic expanse; however, its 2014 population constitutes only 0.23% of China's population (3.18 million). Tibet is a typical agriculture-based autonomous region, and its primary industry contributed over 45% to the economy in the early 1990s. After years of development, Tibet now has a tertiary industry as a foundational economic driver, and this tertiary industry contributed 53.5% to total gross domestic product (GDP) in 2014. Even so, the primary industry remains the largest sector in Tibet, and 43.7% of the working population work in the primary industry. The secondary industry, which includes industry and construction, is the smallest segment of Tibet's national economy; it employs only 14.7% of Tibet's working population. The secondary industry's GDP in 2014 was 33.68 billion yuan, which is quite small compared with China's national GDP of 27,176.45 billion (0.12%) [*National Bureau of Statistics of China*, 2015].

Due to its small scale of energy-intensive industries, Tibet consumes very little energy every year and its consumption of conventional fossil fuels is particularly low. Moreover, because it is covered primarily by forests, lakes, and other natural ecological reserves, Tibet has large carbon sink capacities. For example, Tibet's forests covered 14%+ of its total area in 2015, and its forest stock is 2.09 billion m^3, ranking at the top of Chinese provinces [*The State Council Information Office of China*, 2015]. The forests' ecosystem will absorb 50.65 million tons of carbon every year [*National Energy Administration*, 2014]. Tibet's carbon sink function is larger than its human-induced carbon emissions. Even so, both Chinese central and local governments have taken actions on Tibet's emission reduction and climate change mitigation. In the "Tibet action on climate change and emission reduction during 2014-2015" issued by *Tibet Autonomous Region Government* [2014], the energy consumption intensity (energy consumption per GDP) in 2015 is required to decrease by 2.09% compared with that in 2014, while the CO_2 emissions are required to keep stable with 2010. In the assessment of each province's emission intensity (CO_2 emissions per GDP) reduction by the *National Development and Reform Commission of China* [2015], Tibet had the worst performance among China's 31 provinces.

Given the targets of emission reduction in Tibet autonomous region, a quantitative measure of Tibet's regional CO_2 emissions is urgently needed. However, due to lack of data, this research field is still vacant. Generally speaking, CO_2 emissions of one administrative region could be calculated in three ways: territorial-based, production-based, and consumption-based approach [*Barrett et al.,* 2013], among which, territorial-based emissions are used to account emissions *"taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (page overview.5)"* [*Intergovernmental Panel on Climate Change [IPCC]*, 1996]. We therefore adopt the territorial-based emission scope in this study, as it could describe the emission characteristics as well as emission sources of one region. According to the IPCC, CO_2 emissions can be calculated as activity data (energy consumption/industry products' production) timed by emission factors [*IPCC*, 2006]. Scholars use energy balance tables industrial sectoral energy consumption to calculate the emission inventories of China and its provinces [*Peters et al.,* 2006; *Shao et al.,* 2011, 2016a, 2016b; *Guan et al.,* 2012; *Liu et al.,* 2016]. However, this method can only be used in provinces with consistent energy data, such as Beijing, Shanghai, and Hebei. Tibet is not included in China's energy statistical system. China's National Bureau of Statistics releases national and provincial energy data in its annual "China Energy Statistical Yearbook". The yearbook is the only official energy report in China [*National Bureau of Statistics of China*, 2016a]. There is no Tibet's energy data in the yearbook.

Due to the data missing, previous studies on China's national/provincial inventory excludes Tibet [*Liu et al.,* 2015; *Shan et al.,* 2016; *Wu et al.,* 2017], as well as analysis on China's energy consumption and greenhouse gas emissions [*Fan et al.,* 2015, 2016; *Wang et al.,* 2016; *Wang and Feng*, 2017]. Few studies have focused on Tibet's energy consumption. Only three English-language papers could be found covering Tibet's energy consumption on the Web of Science [*Liu et al.,* 2008; *Ping et al.,* 2011; *Zhang et al.,* 2015], and 11 Chinese documents [*Wang*, 1985; *Cai and Zhang,* 2006a, 2006b; *Wang,* 2006a, 2006b; *Pei and Liu*, 2007; *Wang et al.,* 2007; *Yao*, 2013; *Tang and Chen*, 2015; *Yang and Zheng*, 2015; *Zhao et al.,* 2016] were found on China's National Knowledge Infrastructure datasets. Most of these papers discussed Tibet's sustainable energy development and its carbon sink function, as well as emissions from biomass fuels [*Xiao et al.,* 2015]. *Zhao et al.* [2016] is the only study that has discussed Tibet's human-induced CO_2 emissions so far. These authors estimate the fossil fuel consumption in Tibetan industries and calculate the related CO_2 emissions for the year 2012.

Cities (prefecture-level administrative divisions) are the core targets of climate change mitigation and greenhouse gas emissions reduction. Previous studies have focused almost exclusively on mega-cities and affluent cities in China [*Kennedy et al.,* 2009, 2015; *Hillman and Ramaswami*, 2010; *Chen and Chen*, 2016; *Lu and Chen*, 2016; *Mi et al.,* 2016; *Meng et al.,* 2017]. Although emission inventory construction methods have been developed for cities with limited energy data [*Kennedy et al.,* 2010; *Shan et al.,* 2017], there is yet no research examining CO_2 emissions from Tibet's cities. There are seven cities (prefecture-level administrative divisions) in the Tibet Autonomous Region: Lhasa City, Qamdo City, Xigaze City, Shannan Region, Nagqu Region, Ngari Region, and Nyingchi Region (specific location seen in Figure 3). In this study, we fill this research gap by estimating Tibet's CO_2 emissions and its cities for the first time, by sectoral approach. Our quantitative measure of Tibet's regional CO_2 emissions will provide solid data support for Tibet's actions on climate change and emission reductions.

2. Method and Data Collection

2.1. CO_2 Emission Calculation

In this study, we use IPCC territory administrative CO_2 emissions from Tibet and its seven cities. Our CO_2 emissions include two parts: emissions from fossil fuel combustion (energy-related emissions) and emissions from industrial processes (process-related emissions). The process-related emissions involve CO_2 emissions produced during chemical reactions in industrial processes. As Tibet has only a cement production industrial process, the process-related emissions in this study include only those emissions from cement production. The emissions related to fossil fuel burning to power cement production are counted as energy-related emissions, rather than process-related emissions.

According to IPCC guidelines, energy-related CO_2 emissions (CE_{energy}) are calculated as fossil fuel combustion multiplied by factors; see equation 1.

$$CE_{energy} = \sum_i \sum_j CE_{ij} = AD_{ij} \times NCV_i \times EF_i \times O_i \quad (1)$$

where CE_{ij} refers to CO_2 emissions from fossil fuel *i* combust in sector *j*, and AD_{ij} (activity data) is the burning consumption of fossil fuel *i* by sector *j*. Tibet has a relatively simple energy structure in which only six types of fossil fuel are used (see Table S1, Supporting Information). NCV_i, EF_i, and O_i are net caloric value, the emission factor, and the oxygenation efficiency of fossil fuel *i*, respectively. In this study, we collect these parameters from our previous survey of China's fossil fuel quality [*Liu et al.,* 2015], which are thought to be more accurate regarding China's energy consumption.

CO_2 emissions from the cement process could be estimated in equation 2.

$$CE_{process} = AD_t \times EF_t \quad (2)$$

where AD_t is production of the product, which refers to cement production in this study. The emission factor for cement production (EF_t) is 0.2906 tons of CO_2 per ton of cement production, which is collected from *Liu et al.* [2015] as well.

2.2. Cement Production

Data regarding cement production in Tibet for 2014 was collected from the Tibet statistical yearbook 2015 [*Tibet Bureau of Statistics*, 2015]. In 2014, Tibet produced a total of 3422.48 thousand tons of cement. According to the "Tibet 12th Five-year Plan for Building Materials Industry" [*Tibet Autonomous Region Government*, 2011], there are only seven cement manufacturing companies in Tibet; see Table S2. We use Tibet's 2014 cement production to scale each plant's production and total up by regions. Then, we obtain the cement production for each city, as shown in Table S3.

2.3. Energy Consumption

Unlike provinces with consistent energy statistics, the energy consumption data can be collected from the energy balance tables in China energy statistical yearbooks, only limited information about Tibet's fossil fuel consumption can be found online. Thus, we estimate fossil fuel consumption for Tibet and its seven cities in a bottom-up approach. We collect the consumption of specific energy types of Tibet from multiple sources, such as government reports, news reports, and literature.

As the abundant hydro power in Tibet, electricity from hydro power station plays the dominant part in Tibet industrial and residential energy consumption, which also suppress the fossil fuel usage in Tibet. Most emissions from fossil fuel come from the industrial production and transportation.

2.3.1. Coal

2.3.1.1. Industrial Coal Consumption

There are no official reports on Tibet's coal consumption statistics. Approximately 85% of Tibet's coal consumption is associated with cement plants to provide power; the remaining 15% is used for restaurants and residences [*Zhao et al.,* 2016]. Therefore, we use Tibet's cement production to estimate coal consumption in equation 3.

$$CC_{total} = \frac{CC_{cement}}{85\%} = \frac{CP_{clinker} \times uCC_{clinker}}{85\%} \quad (3)$$

where CC_{total} indicates total coal consumption in Tibet; CC_{cement} presents the coal consumption for cement production in Tibet; CP_{cinker} means cement-clinker production in Tibet; $uCC_{clinker}$ is the coal consumption for the unit cement clinker output. As there is no cement-clinker production in Tibet's statistical yearbook, we use the national cement-clinker production ratio to estimate Tibet's cement production. According to "The 12th Five-year Plan for Building Materials Industry" [*Ministry of Industry and Information Technology of China*, 2011], the national new dry cement-clinker production in 2010 was 1260.00 million tons, taking 81% of overall cement clinker. Thus, total cement-clinker production in 2010 is estimated as 1555.56 (=1260/81%) million tons. At the same time, the national total cement production is 1880.00 million tons, which means that the average cement-clinker production ratio is approximately 82.74% (=1555.56Mt/1880.00Mt) in China. We use the national average ratio to estimate Tibet's cement-clinker production as 2831.85 (=3422.48 × 82.74%) thousand tons in 2014. According to the same report, average coal consumption of cement-clinker production is 160 kg per ton clinker production in China. We adopt the national average value and calculate the entirety of Tibet's coal consumption as 533.05 (=2831.85 × 160/85%/1000) thousand tons of coal.

2.3.1.2. Residential Coal Consumption

Among the total coal consumption, 453.10 thousand tons are consumed in cement plants and the remaining 79.95 thousand tons are consumed for residential usage. We allocate the residential consumption of coal to each city based on its population in 2014. The populations of each administrative division are collected from the sixth national population census [*National Bureau of Statistics of China*, 2012].

2.3.2. Oil

2.3.2.1. Diesel Consumption in Thermal Power Plants

The total thermal power generation of Tibet was 149 million kWh in 2014 [*National Bureau of Statistics of China*, 2016a]. The State Grid Tibet Electricity Power Company Limited has two thermal power plants in Tibet: the Ngari thermal plant and the Dongga (Lhasa) thermal plant. The Ngari thermal plant has four 2500 kW diesel generating sets [*State Grid Tibet Electricity Power Company Limited*, 2015], and the total installed capacity of the Ngari thermal plant is 10 thousand kW. The Dongga (Lhasa) thermal plant has six 11,500 kW diesel generating sets before 2010, China's Huaneng Group invested in another nine 11,500 kW sets in 2010, bringing the total installed capacity of the Dongga (Lhasa) thermal plant to 172.5 thousand kW. Therefore, we assume that the electricity generated by the Ngari thermal plant was 8.16 million kWh in 2014, whereas the electricity generated by the Dongga thermal plants in Lhasa was 140.84 million kWh.

The fuel consumption of the diesel generating set is approximately 190 – 250 g/kWh [Weifang Chengfeng Power Equipment CO. Ltd; *Xiao*, 2001; *Bao and Tian*, 2014], which means that in producing 1 kWh electricity, the generating set will combust 190 – 250 g of diesel oil. Considering the low combustion efficiency in the plateau, we adopt a high threshold value of 250 g/kWh in this study. In this manner, we calculate that the Dongga (Lhasa) thermal plant burned 35.21 (=140.84mkWh × 250 g/kWh/1000) thousand tons of diesel oil in 2014, whereas the Ngari thermal plant burned 2.04 (=8.16mkWh × 250 g/kWh/1000) thousand tons.

2.3.2.2. Other Refined Oil Consumption in Transportation Sector

Tibet consumed approximately 745 thousand tons of refined oil in 2012, which consists mainly of diesel oil in road transportation and thermal power plants (410 thousand tons), gasoline in road transportation (310 thousand tons), diesel oil in railway transportation (10 thousand tons), and kerosene in air transportation (15 thousand tons). Among the 745 thousand tons of consumption, 600 thousand tons were sold by China's National Petroleum Corporation (CNPC) [*Zhao et al.*, 2016]. In 2014, CNPC sold 786.30 thousand tons of petroleum products in Tibet [*National Development and Reform Commision of China*, 2016]. We estimated total petroleum product consumption at 976.32 (= 786.30/600 × 745) thousand tons in 2014, including diesel oil burned in thermal power plants, which were identified previously as the 37.25 thousand tons calculated above. The consumption levels of diesel oil for road transportation, diesel oil for railway transportation, gasoline for road transportation, and kerosene for air transportation are estimated as 500.06, 13.11, 406.26, and 19.66 thousand tons, respectively.

We allocate diesel oil and gasoline consumption in road transportation to each city according to cities' tertiary industry GDP (including transport, storage and post as dominating contributors). The diesel oil consumed for railway transportation and kerosene for air transportation are calculated in Lhasa due to Lhasa's dominant volume of freight traffic and passengers in Tibet (see Table S4).

2.3.3. Residential Gas Usage

2.3.3.1. Natural Gas and Liquefied Petroleum Gas Consumption in the Lhasa Urban Area

The "Gas Tibet" project was launched by Qinghai Oilfield, CNPC in 2010 to bring natural gas to Lhasa for the first time. Natural gas consumption increased 10 times in the last 3 years [*Ren and Yang*, 2014]. The total natural gas supplied to Lhasa reached 160 thousand m^3 in 2014. In addition, Tibet also consumed a small amount of liquefied petroleum gas (LPG) in its urban area, approximately 62.48 thousand tons in

Table 1. Conventional Energy Consumption and Cement Production of Tibet and Its Cities, 2014

Division	Cement	Coal	Diesel	Gasoline	Kerosene	LPG	Natural gas
Unit	10^3 tons						10^3 m^3
Lhasa	1789.80	251.85	260.32	172.23	19.66	62.48	160.00
Qamdo	179.62	41.29	49.96	40.59	—	—	—
Shannan	1162.22	162.63	44.85	36.44	—	—	—
Xigaze	221.79	48.09	71.89	58.40	—	—	—
Nagqu	-	12.31	51.32	41.69	—	—	—
Ngari	69.04	11.68	20.06	14.64	—	—	—
Nyingchi	-	5.20	52.03	42.27	—	—	—
Total	3422.48	533.05	550.42	406.26	19.66	62.48	160.00

2014 [*National Bureau of Statistics of China*, 2016a], which are all assumed to be consumed in Lhasa's urban households.

In summary, the levels of conventional energy consumption and cement production in Tibet and its cities in 2014 are shown in Table 1. We use these activity data for CO_2 emissions estimation in the following section.

3. Results

3.1. Tibet's Total CO_2 Emissions in 2014

In 2014, Tibet emitted a total of 5.52 million tons of CO_2 related to fossil fuel combustion and cement production. These emissions were relatively small both in their absolute amounts and in terms of the proportion of national emissions (9438.45 million tons), which stands at 0.06% of China's total emissions [*CEADS*, 2016]. The small emissions amount results from Tibet's limited industry but also from its renewable-dominant energy structure. Tibet is rich in renewable energy, such as hydro energy, wind power, and solar energy [*Tang and Chen*, 2015]. In fact, 3.24 billion kWh of the electricity generated in Tibet was from renewable energies in 2014, accounting for 89.94% of total electricity generation. Hydro energy contributed 80.64% of this amount (2.90 billion kWh). Only 10.06% (0.36 billion kWh) of electricity was generated in fire-powered plants. Tibet's renewable energy proportion in the energy mix was much higher than the national average level of 11.30% in 2014.

Apart from non-fossil fuel energies, diesel and gasoline consumption are Tibet's main sources of energy-related emissions (see Figure 1a). These two energy types contributed 31.42% (1.73 million tons) and 21.94% (1.21) to total CO_2 emissions, respectively, in 2014. In addition, coal is responsible for only 975.48 thousand tons of CO_2, accounting for 17.68% of total emissions primarily because of Tibet's simple energy structure. This is significantly different from China's overall emission structure and from the structures in other provinces: coal and its related products dominate energy consumption (65.60%) and CO_2 emissions (77.21%) and is burned mainly in coal-based fire-powered plants for power. In Tibet, as discussed above, coal is consumed exclusively in cement plants and for residential usage, the only two fire-powered plants are diesel-based power plants. This is a result of Tibet's limited coal sources and low coal production. Almost all the coal used in Tibet are imported from its nearby provinces. In 2014, 625.5 thousand tons of coal are imported to Tibet according to "China Coal Industry Yearbook 2014" [*China Coal Information Institute*, 2014]. Considering the factor of stock changing and statistical error, our estimation of 533.05 thousand tons' coal consumption is relatively accurately.

The cement process is another large contributor to Tibet's CO_2 emissions, accounting for 18.02% (994.57 thousand tons) in 2014. This percentage is much higher than the national average level of 7.67% in 2014.

From the sectorial perspective, we find that transportation and cement production are two primary contributors to CO_2 emissions (Figure 1b). Indeed, 50.48% (2.79 million tons) of total emissions are associated with road transportation, which is mainly induced by gasoline usage in private cars and passenger coaches and by diesel used in cargo trucks. Cement production contributed 33.05% (1.82 million tons) to total emissions. The cement production emissions include two parts: emissions from the cement process (994.57 thousand tons), which is the same as the cement process in Figure 1a; and emissions from coal combustion in cement

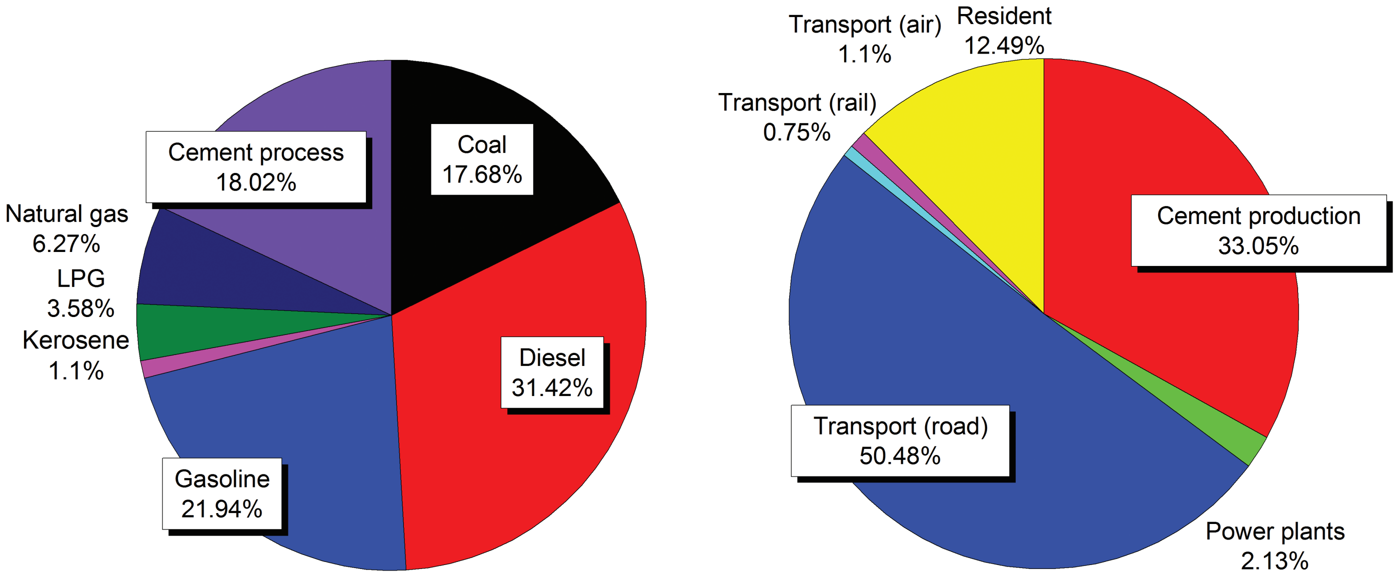

Figure 1. CO_2 emissions from fossil fuel types and sectors in Tibet, 2014.

plants for power (829.17 thousand tons). The remaining 16.47% of CO_2 emissions are associated with air transportation, rail transportation, power plants, and residential consumption.

Figure 2 provides a detailed illustration of energy structures in different sectors' CO_2 emissions. This figure shows that in road transportation, 56.54% emissions are from diesel consumption (mainly used in cargo trucks). The remaining 55.54% is induced by gasoline combustion in private cars and passenger coaches. Apart from electricity, residents in Tibet consumed a substantial amount of LPG, which contributes 28.64% of the total residential emissions. LPG and natural gas (50.13%) are consumed only in Lhasa City, having benefited from the "Gas Tibet" project since 2010 [*Ren and Yang*, 2014]. Households in rural and less-developed areas (particularly Nagqu, Ngari, and Nyingchi) use coal as their main energy source for heating and cooking due to the lack of electricity and gas. This segment of coal consumption emitted 146.31 thousand tons of CO_2 in 2014.

We calculate Tibet's per capita CO_2 emissions at 1.74 tons and its emission intensity at 0.60 ton per thousand yuan in 2014. Per capita CO_2 emissions in Tibet are remarkably lower than the national level of 6.90 tons [*CEADS*, 2016]. Tibet is one of the least developed provinces in China, as most of its residents continue to maintain a farming-based lifestyle, which consumes less energy than urban lifestyles. However, Tibet's emission intensity is much higher than the national level of 0.15 ton per thousand yuan because of the low combustion heat value in the plateau, backward production technologies in industrial system and Tibet's simple industrial structure. Heavy industries account for the lion's share of the 58.86% in Tibet's overall industrial output. Cement production is the primary contributor, accounting for 34.05% of heavy industrial output. Tibet's emission intensity is close to Ningxia's (0.52 ton per thousand yuan) due to the nearby geographical location and similar simple industry structure.

3.2. Tibet's Historical CO_2 Emissions Growth

Based on the CO_2 emissions in 2014, this study estimates Tibet's time-series emissions from 2003 to 2013 with its energy consumption/cement production increasing rate. The cement process-, LPG-, and natural gas-related emissions are calculated with their own historical emissions [*National Bureau of Statistics of China*, 2016a]. The emissions from coal consumption are calculated based on the cement production increasing rate [*National Bureau of Statistics of China*, 2016b]. The refined oil consumption in Tibet increased 13% per year steadily [*Tibet Autonomous Region Government*, 2007], we use the ratio to estimate Tibet's CO_2 emissions from diesel, gasoline, and kerosene.

Our results find that Tibet's CO_2 emissions in 2003 are about 1300 thousand tons, and then increased smoothly at a speed of 14+% per year, see Table S5. With the growth rate of 15%, we estimate Tibet's CO_2

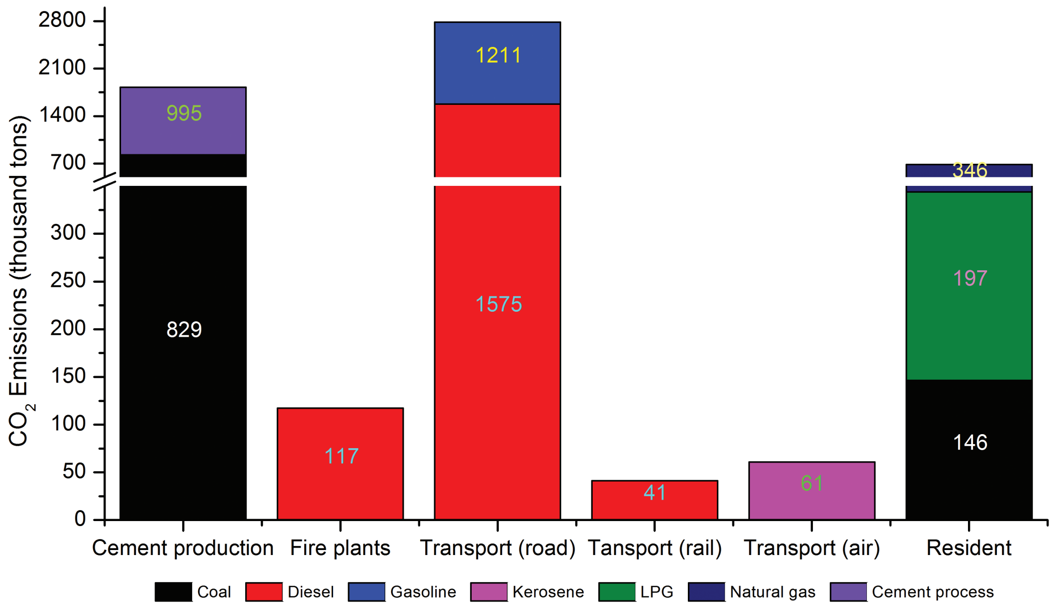

Figure 2. Tibet CO_2 emissions in 2014 by different sectors and by energy types. Diesel and coal are main fossil fuel used in Tibet, and cement production and road transport contribute the most to the CO_2 emissions.

emissions in 2015 as 6346 thousand tons. However, benefited from the "Gas Tibet" project, the natural gas consumption in Tibet increased sharply in 2015, reached 13,460 thousand m^3 [*China Energy Web*, 2016; *National Bureau of Statistics of China*, 2016a]. Considering this, we reckon Tibet's total CO_2 emission would surpass 35,000 thousand tons in 2015.

3.3. The CO_2 Emissions of Tibet's Cities

We calculate the CO_2 emissions of seven of Tibet's cities in 2014, as shown in Figure 3. The pie chart in the top right corner presents the emission proportion of each administrative division (in thousand tons). The detailed emissions from energy sources and sectors are shown in Table S6.

This figure shows that over half of Tibet's CO_2 emissions come from Lhasa City. Lhasa is the capital and the largest and most developed city in Tibet, contributing 37.73% to Tibet's economic growth in 2014. Therefore, Lhasa has the most complex emission structure of all the cities, as shown in Figure 4. Like Tibet's emission structure, approximately 83% of Lhasa's emissions are from cement production (38.28% or 953.73 thousand tons) and road transportation (44.54% or 1.11 million tons). Lhasa is the largest cement production base in Tibet, with four cement plants, and produces 52.30% of Tibet's total cement production. Lhasa is also the entrepot of Tibet, with high volumes of passenger and freight traffic. As discussed above, LPG and natural gas are used in Lhasa's urban households, and these two energy types account for 95.22% of Lhasa's CO_2 residential emissions. This percentage is substantially higher than China's average level of 37.90% in 2014 [*National Bureau of Statistics of China*, 2016a].

The Shannan region is another large CO_2 emitting region in Tibet, accounting for 16% of emissions. Most of its CO_2 emissions are also related to cement production (69.96%, 619.32 thousand tons) and road transportation (28.23%, 249.87 thousand tons). Lhasa and Shannan have the highest per capita emissions and emission intensities among Tibet's cities. The per capita emissions of the two divisions are 4.93 and 2.54 tons, respectively. The value is close to that of Sichuan province (4.19 tons) and Yunnan province (4.14 tons), areas that are contiguous to Tibet. The emission intensity of Lhasa and Shannan is 0.84 and 0.88 tons per thousand yuan, respectively. The high emission intensity is caused by a large amount of cement production in these administrative divisions.

Nagqu and Nyingchi regions are the only two divisions with no cement production in Tibet. These two cities' emission intensities are therefore the lowest (0.37 and 0.32, respectively). Nagqu is a pure pasturing zone: 73.99% of its area (333.33 thousand km^2) is meadow. Nyingchi is a typical mountainous region in Tibet: the

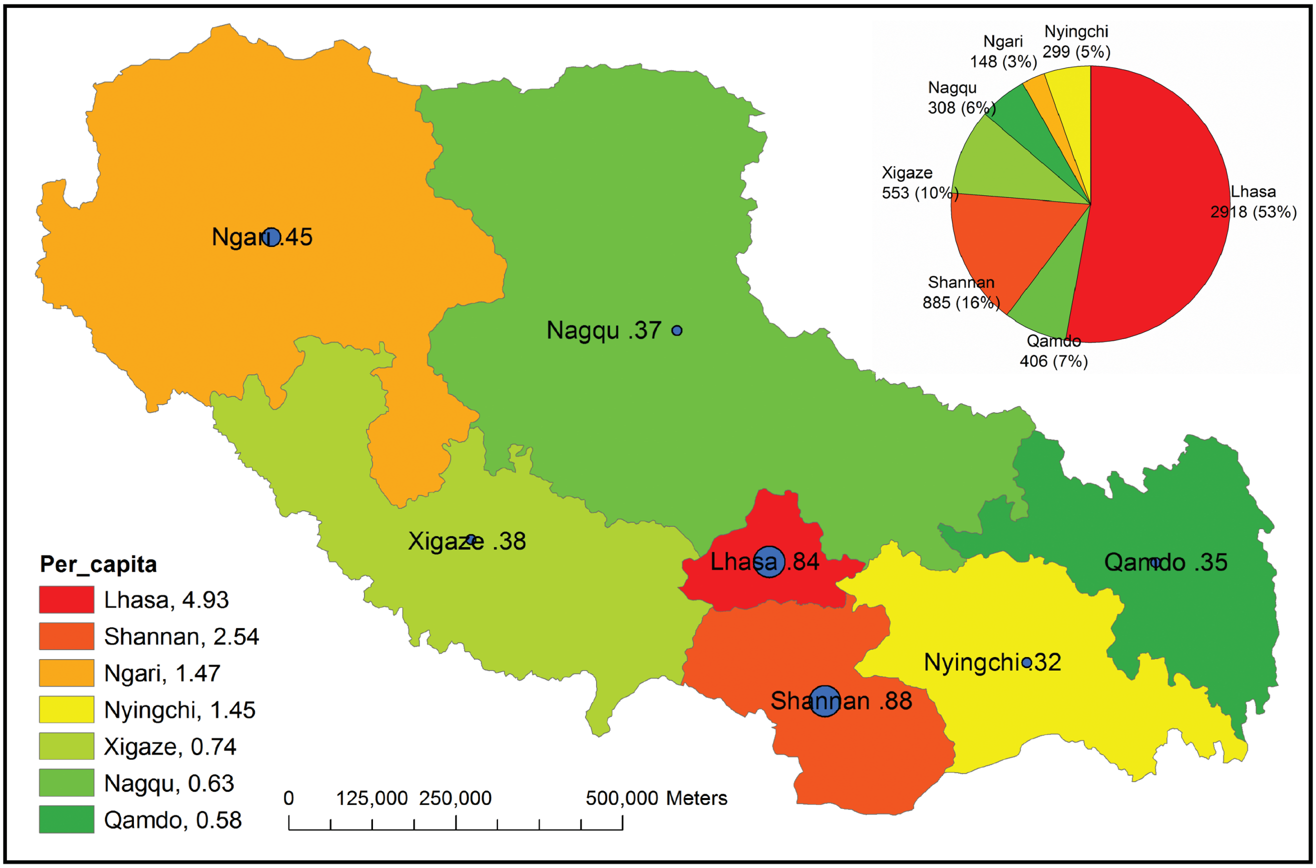

Figure 3. CO_2 emissions from seven cities in Tibet, 2014. The colors of the map show the per capita emissions (CO_2 emissions/population, in ton) of each city. Greener city has a lower per capita emission while redder city have a higher one. The Blue circles represent emissions intensity (CO_2 emissions/total GDP) for each city, bigger circle refers to a higher emission intensity. The numbers on the map shows the emission intensity of each city (in ton per thousand yuan), for example, the emission intensity of Lhasa is 0.84 ton per thousand yuan.

Himalayas and the Nyenchen Tanglha Mountains run through it. Nyingchi's forest coverage rate is 46.0%, and 80% of Tibet's forest is in Nyingchi. There is very little industry in Nagqu and Nyingchi regions.

4. Discussion and Conclusion

Tibet's autonomous region has always been absent in energy statistics and CO_2 emissions accounting. Previous studies on China's national and provincial emissions accounting typically ignore Tibet. In this paper, we estimate its energy consumption according to limited online documents and calculate Tibet's energy- and process-related CO_2 emissions of Tibet and its seven cities in 2014 for the first time. This study has achieved the following give main findings.

1. Tibet emitted 5.52 million tons of CO_2 in 2014; 18% of these emissions are associated with the cement production's process emissions, and the remaining 82% from fossil fuel combustion.
2. Diesel and gasoline are two dominating energy types in Tibet's emission structure. Approximately 90% of Tibet's CO_2 emissions in 2014 are associated with cement production and road transportation.
3. The per capita emission of Tibet in 2014 was 1.74 tons, which is remarkable lower than the national average level, whereas the emission intensity of Tibet is relatively high, at 0.60 ton per thousand yuan in 2014.
4. Lhasa City and the Shannan region are two large CO_2 contributors among the seven cities in Tibet. They also have the highest per capita emissions and emission intensities. The Nagqu and Nyingchi regions emit little CO_2 every year as a result of their farming/pasturing-dominated economies.

The detailed analysis of Tibet's emission characteristics implies that possible measures regarding Tibet's CO_2 emissions reduction could be taken as follows.

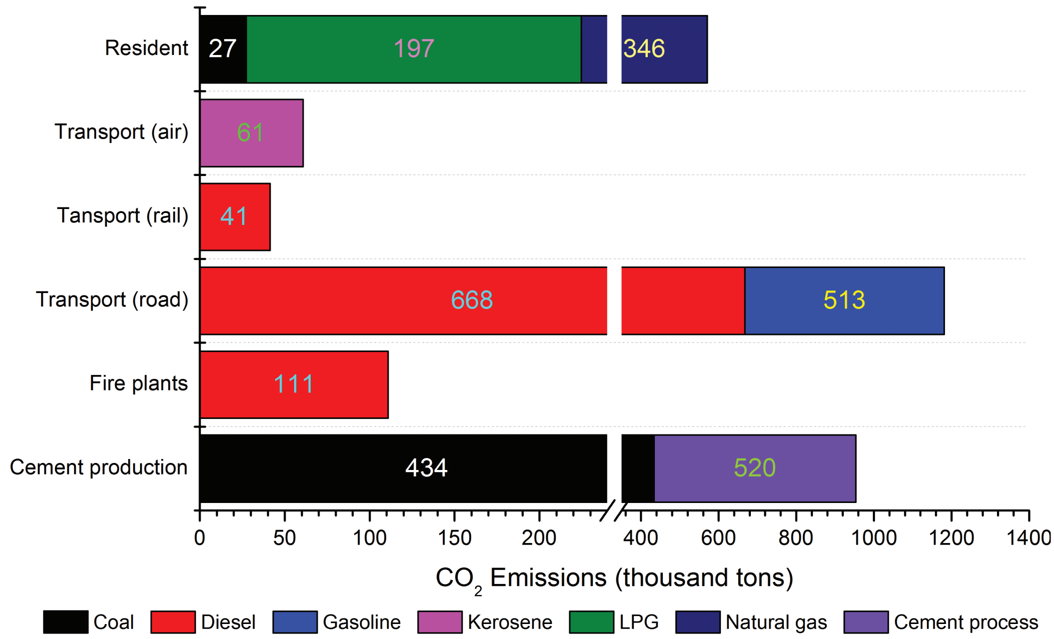

Figure 4. Lhasa CO_2 emissions in 2014. As the capital and largest city of Tibet, Lhasa has the most complex emission structure of all the cities. Transportation and cement production are the primary contributor to Lhasa's CO_2 emissions. LPG and natural gas used in households also emit lot of CO_2.

1. Despite Tibet's per capita emissions is much lower than the national average level, there is a certain amount of scattered coal combusted by households in Tibet's rural regions. Tibet should replace residential coal usage in rural and less-developed regions by natural gas. The "Gas Tibet" project has met with huge success in Lhasa city during the past 3 years and increased its natural gas consumption by 10 times. We suggest that the project should be continued and expanded to other administrative divisions in Tibet. Coal is more carbon-intensive energy type than natural gas, and replacing coal by natural gas in residential usage could thus reduce Tibet's CO_2 emissions effectively.
2. Considering the emission intensity in Tibet is relatively high, Tibet should improve its industry production process. As the only energy-intensive industrial process in Tibet, cement production contributes substantially to emissions each year, although Tibet's cement production is relatively limited compared with other regions in China. Measures such as improving the energy combustion efficiency/combustion heat value, reducing the unit energy consumption in cement production could lower Tibet's emission intensity.
3. Tibet could weed out the behindhand generator set in the fire-power plant. We suggest replacing the four 2500 kW diesel generating sets in the Ngari thermal plant by 11,500 kW or more advanced sets. The advanced sets have lower unit energy consumption.
4. Tibet could maintain the development of renewable energies. Notably, Tibet has abundant water resources and thereby great potential to develop its renewable energy, particularly via hydropower. As Tibet has developed its hydropower capability, Tibet's green electricity generation increased rapidly from 1.72 in 2010 to 3.24 billion kWh in 2014. The percentage in total electricity generation also increased from 81.81% to 89.94% during the same period. Although energy consumption and CO_2 emissions in Tibet are much lower than in other provinces, Tibet's role in national climate change mitigation should not be underestimated. Because of its high potential capacity of hydropower, Tibet is more likely to act as the electricity exporter and to ease electricity shortage and decrease energy consumption in other regions. Tibet should continue this increasing trend and develop its renewable energies in the future. Despite all these, conventional fossil fuels would still play an important role in Tibet's energy structure. Booming infrastructure development in Tibet, particularly in road construction, would directly bring about a rise in diesel and gasoline consumption, thereby increasing emissions. Tibet's energy and emission structure would be more likely to change in the future.

Due to the data availability, this research only considers several energy types (coal, diesel, gasoline, kerosene, LPG, and natural gas), as well as several sectors (transportation, cement production, residential usage) in the emission accounts. In the future work, we would detail the Tibet's CO_2 emissions if more detailed energy data could be collected. Also, we would like to conduct the time series CO_2 emissions research for Tibet and try to categorize emissions changes patterns.

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