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Regional disparity in clinker emission factors and their potential reduction in China

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ABSTRACT:

Detailed analysis the disparity and reduction potential of clinker emission factors at the provincial level is important for regional reduction policies. Using the surveyed data from 185 new suspension and pre-heater (NSP) process lines and 69 Shaft kiln lines, this study firstly analyzed the disparity in emission factors based on production process, production scale, and regional distribution in 2015. We found that the emission factor of the Shaft kiln process (898.24 kg/t) is higher than that of the NSP process (858.59 kg/t), and that small-scale production lines have higher emission factors than large-scale lines both for the two process. China's clinker emission factors increase from the eastern to the western regions. Then we estimated the reduction potential of structural adjustment, raw material substitution, and energy saving and fuel substitution in regional emission factors by 2030. The result shows that emission factors of the

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surveyed provinces will decrease by 101.41-174.60 kg/t compared to the values in 2015, which is mainly contributes by energy saving and fuel substitution (65.98%), and raw materials substitution (25.72%). And structural adjustment contributes only a small part reduction for most investigated provinces. The national average emission factor is estimated to be 715.33 kg/t in 2030, which indicates a reduction of 16.65%. These results can provide valuable feedback to government officials on the effectiveness of existing measures and also serve as a reference for future decisions on emission reduction polices.

Keywords: Cement clinker; Emission factor; Reduction potential; Disparity; China

1. Introduction

The cement industry is characterized by its high usage of mineral resources and fossil energy and correspondingly high emissions of greenhouse gases. As a major carbon-emitting industry, it accounts for approximately 7% of the total global carbon emissions (Deja et al., 2010). China is both the largest producer of cement and the highest emitter of CO_2 in the world. It has ranked first globally in cement output since 1985. In 2016, China's cement output was 2410 million tons (Mt) (NBS, 2017), accounting for 59.16% of the total global cement output (U.S.G.S, 2018). China's cement sector emitted approximately 1270 Mt of CO_2 in 2011 (Gao et al., 2017a; Shen et al., 2015). The rapid expansion of the cement sector is associated with increasing resource and energy consumption and pollution, thereby posing a severe challenge to the sustainable economic and social development of China.

Several studies have investigated the carbon emission generated by China's cement industry. These studies have estimated the carbon emissions based on different calculation methods, production processes, and material or fuel consumptions; thus, the results differ

greatly from each other. Wei et al. (2012) and Liu et al. (2014) analyzed and compared the methods for the calculation of carbon emission in China's cement industry proposed by scholars domestically and internationally. Hu et al. (2015) analyzed the emissions generated by two production processes, namely, a new suspension and pre-heater (NSP) kiln and Shaft kiln. Based on production data from different enterprises, Shen et al. (2014) studied the emission factors of clinkers and cement in the major production processes. Zhao and Wei (2013) compared the emission factors between two production scales of 2500 tons/day (t/d) and 5000 t/d. However, few studies have examined the disparity in regional carbon emissions. Research into the regional disparity in the emission factors of cement clinkers and underlying reasons for such variations will aid in the drafting of appropriate regional policies for emission reduction.

To reduce the emission factor of cement clinker, scholars have conducted in-depth research on emission reduction with respect to fuel consumption and production processes. Several researchers have examined opportunities for reducing carbon emissions in the cement sector by means of technological modernization and improved energy efficiency. Ali et al. (2011) studied the energy intensity of different cement kiln processes. Compared with the wet-process kiln, a dry-process kiln can reduce power consumption by 13% and fuel consumption by 28% (Avami and Sattari, 2007). Energy-efficiency-asia (2010) compared the heat consumed by different types of cement kilns and auxiliary devices and found that a multi-stage cyclone preheating system could reduce energy intensity. Therefore, replacement of outdated kilns with the NSP process kiln is effective for reducing carbon emissions. Previous studies have analyzed the energy intensity of different types of kilns in terms of

production processes, but few have investigated the differences in energy intensity between production lines at different production scales and the emission reduction potential of large-scale production.

Wastes and by-products can be utilized as constituents of the final product and components of the kiln feed for cement production (Trezza and Scian, 2000). Some industrial wastes with high CaO, SiO_2, and Fe_2O_3 content can be used as calcium, silicate and iron sources in the production of cement clinker. Numerous studies have reported the utilization of carbide slag (Li and Li, 2010; Liu et al., 2014), steel slag(Carvalho et al., 2017; Iacobescu et al., 2011; Iacobescu et al., 2013; Saade et al., 2015; Zhang et al., 2011), lead slag (Onisei et al., 2012), phosphorous slag (Allahverdi et al., 2016; Gao et al., 2008; Li et al., 2000), copper slag (Kalinkin et al., 2012), magnesium nickel slag (Maes and Belie, 2017; Tan et al., 2016; Zhang et al., 2011; Zhang et al., 2017), coal fly ash (Darsanasiri et al., 2018; Shwekat and Wu, 2018; Xu and Shi, 2018), and waste sludge (Lin et al., 2017; Rodríguez et al., 2013; Valderrama et al., 2013) as alternative materials in cement clinker production. The main mix materials used in China include combustion ashes, metallurgical slag, chemical slag, and other mineral components. The annual output of industrial byproducts that can be used in cement production in China exceeded 2 Bt (Zhang et al., 2013). However, it is only used in a small number of investigated enterprises, and the substitution rate is quite low; The current rates of replacement by alternative raw materials and fuels in China's cement industry are 1.30% and 1.80%, respectively (Gao, 2018; Gao et al., 2017a; Ke et al., 2012), only a 2.37% reduction has been achieved in calcination emissions (Gao et al., 2017a). There is a big difference between the scale at which raw materials and fuels are substituted in China and

that in developed countries.

Detailed analysis the regional disparity and reduction potential of clinker emission factors, which is important for both scientific research and design of emission control policies has been lacking. Objective quantification of the CO_2 emission factors of regional clinkers, identification of the disparity in their values, and evaluation of ways to reduce them are warranted. Based on a sampling survey that considers the production processes and scales, the variety and quantity of substitute materials and fuels, and the energy saving technologies application plan in different regions, the current study aims to fill this gap by analyzing the scale changes and regional differences of clinker emission factors, evaluating the potentials and methods for emission reduction in the surveyed provinces in 2030, thus aiding in decision-making regarding regional emission reduction.

To achieve these objectives, this study was divided into four sections. The survey data and clinker emission calculation method are described in Section 2; in Section 3 comparison of clinker emission in provinces and scales; Section 5 evaluates the emission reduction methods and their reduction potential; and conclusions are discussed in Section 5.

2. Data sources and calculation methods

2.1 Data sources

During the years 2011–2015, a total of 254 production lines (185 NPS kilns and 69 Shaft kilns), which accounted for 14.96% of China's clinker production, were surveyed in the 22 provinces. The locations of the plants are shown in Figure 1. The surveyed data consist of four sections. The first section contained basic information questions related to enterprise name, geographical location, number and scale of production lines, production process. The

second section mainly included production data: annual output of clinker, annual consumption of fuels, power consumption by the three production stages, and power generated by waste heat. The third section consisted of questions related to chemical composition of raw materials, raw meals, clinkers, and fuels, fuel industry analysis, and proportioning of raw materials. The forth section requested information on whether the facilities had adopted any of the 32 recommended energy-saving and 3 material and fuel substitution measures and, if not, the reason for this and any future plans to adopt new technologies.

Figure 1 Distribution of the surveyed cement production plants

In order to reflect the real carbon emissions and reduce errors, all data items used are annual average values surveyed under normal production status. And the abnormal values were identified and revised by considering the local realities. The clinker production, average fuel intensity, raw meal intensity, chemical compositions of raw meal and clinker, raw materials substitution and waste heat power generation (WHPG) in NSP kilns and Shaft kilns are listed in Table S1. The NSP kilns accounted for 94.98% clinker production of the surveyed samples, and the remaining 5.02% of production was from Shaft kilns. These proportions were similar to the overall structure of China's cement industry. The survey data for average fuel intensity, power intensity and WHPG of the NSP kilns and Shaft kilns were close to the national published value. Additionally, the composition of raw meals and clinkers data from both of the two production process are also fall within their ranges (Zhou and Peng,

2005). Thus, the surveyed samples represent the present performance of China's cement industry.

2.2 Methods for the calculation of emission from production lines/scales

The carbon emissions from cement clinkers comprise three components: process-related, fuel-related, and power-related emissions (Mikulčić et al., 2011). Process-related emissions refer to CO_2 emissions arising from the decomposition of carbonate minerals. Calcium carbonate and magnesium carbonate decompose into Cao, MgO, and CO_2 during clinker calcination. The calculation approach is indicated in Formula (1).

$$EF_{pr} = Ra_{co2} \times r_a \qquad (1)$$

Here, EF_{pr} represents the process-related emission factor of clinker (kg/t), r_a is the raw meal intensity (kg/t), and Ra_{co2} is the carbon content of raw meals (%), which is based on the proportioning of raw materials and the chemical composition of their carbonate materials (Gao et al., 2017a).

Fuel-related emissions refer to the CO_2 emissions arising from the burning of fuels during the calcination of clinkers. This calculation can be made using Formula (2).

$$EF_{fu} = FI_{coal} \times EF_{coal} \qquad (2)$$

Here, EF_{fu} represents the fuel-related emission factor of clinker (kg/t), FI_{coal} is the fuel intensity (kgce/t), and EF_{coal} is the fuel emission factor (kg/kgce) (IPCC, 2006).

Power-related emissions *(EF_{po})* refer to the CO_2 emissions arising from the consumption of power during the grinding of raw materials and calcination of clinker and reduce the power generated by low-temperature waste heat. Usually, different regions use the same calculation method (Formula 3).

$$EF_{po} = (PI_{ele} - PG_{was}) \times EF_{ele} \quad (3)$$

Here, EF_{po} represents the power-related emission factor of clinker (kg/t), PI_{ele} is the power intensity (kWh/t), PG_{was} is the power generated by low-temperature waste heat (kWh/t), and EF_{ele} is the regional power emission factor (kg/kWh) (NDRC, 2012).

The emission factors *(EF_j)* of production lines (*j*) can be made using Formula (4). Sequentially calculated the emission factors of production scales (EF^q) by considering the weight of clinker output (C^i_j) of each production line (*j*) with the same scale ($i=q$) (Formula 5).

$$EF_j = EF_{jpr} + EF_{jfu} + EF_{jpo} \quad (4)$$

$$EF^q = \sum (EF^i_j \times \frac{C^i_j}{\sum_{i=q} C^i_j}) \quad (5)$$

2.3 Method for the calculation of emissions from regional clinkers

We proposed the three tiers of integration framework to estimate regional emission factors from the surveyed clinker production lines (Figure 2). After obtaining the emission factors relevant to all the surveyed lines, we sequentially calculated the emission factors of regional different processes by considering the weight of each of their clinker outputs. According to the proportion of clinker output of Shaft kilns and NSP kilns in the region, the emission factor (EF_r) for province was then integrated (Formula 5).

$$EF_r = \frac{C_{nr}}{C_r} \sum (EF_{jnr} \times \frac{C_{jnr}}{\sum C_{jnr}}) + \frac{C_{sr}}{C_r} \sum (EF_{jsr} \times \frac{C_{jsr}}{\sum C_{jsr}}) \quad (5)$$

Here, C_{nr} and C_{sr} represent the regional NSP ($_n$) and Shaft kiln(*s*) clinker output (kt), C_r is the regional clinker production (kt), C_{jnr} and C_{jsr} stands for the clinker output of surveyed NSP and Shaft production line *j* in region *r* (kt), EF_{jnr} and EF_{jsr} are their production line emission factors (kg/t).

Figure. 2 The framework of three tiers regional emission integrated system

3. Analysis of disparity between carbon emissions from cement clinkers

3.1 Analysis of disparity between emissions with respect to production processes and scales

According to the survey data and the above calculation method, the main emission indexes and emission factors of different processes and scales are listed in Table S2. Among the major indexes of clinkers (Table S2), the CaO content (65.26%) for the NSP process is higher than that (64.44%) for the Shaft kiln process, and the MgO content differs slightly between the two production processes. With respect to substitute materials, the Shaft kiln process reduces carbon emissions (by 10.59 kg/t) more effectively than the NSP process (by 7.58 kg/t). Therefore, the process-related emission factor (521.00 kg/t) of the Shaft kiln process is lower than that (529.33 kg/t) of the NSP process. The power intensity of the NSP kiln process are slightly higher than those of the Shaft process, whereas WHPG are greater. Correspondingly, power-related emissions of the NSP kiln process are lesser than those of the Shaft process, and the fuel-related emissions are also lesser. The fuel-related emission of the Shaft kiln process is 319.67 kg/t and that of the NSP process is 291.74 kg/t. Thus, with respect to production processes, the emission factor of clinkers for the Shaft kiln process (898.24 kg/t) is higher than that for the NSP kiln (858.59 kg/t). This shows that the replacement of Shaft kiln by NSP kiln is one of the methods to reduce clinker emission factor.

In addition to the choice of process, the scale of production will have an impact on fuel and power-related emissions. In order to study the effects of changes of scale upon the emission factors, this paper classifies the production lines of the NSP kiln into five types, and classifies the production lines of the Shaft kiln into four types (Table S2). As shown in Table S2, in both production processes, fuel and power intensity tend to decrease at larger scales of production (Gao et al., 2017b; Zhao and Wei, 2013). For NSP kilns, the fuel and power intensity of >5000 t/d production lines were 104.79 kgce/t and 58.20 kWh/t, which were 15.17 kgce/t and 16.10 kWh/t lower, respectively, than those of <2000 t/d production lines. The WHPG was also higher for lager production lines as they are basically equipped with a low-temperature waste heat power generation system. Thus, the fuel-related and power-related emissions were decreased to 276.65 and 31.23 kg/t for lines with production of >5000 t/d. Thus, it's mass production that has reduced the fuel-related and power-related emissions for both of the two processes.

As shown in Table S2 , the CaO or MgO content of the clinkers does not vary with the changes in production scale; in the NSP process, average CaO content is >65% at all production scales, whereas those of the Shaft kiln process are all <65%. The difference in process-related emissions arising from the different CaO content of clinkers in the two production processes is 6.43 kg/t. For the NSP process, the MgO content of the clinkers varies by 2% across different production scales and is consistently lower than that for the Shaft kiln process. As mentioned before, the chemical composition of clinker is different between NSP kiln and Shaft kiln, but there is no obvious change under different scales of the same process. The difference of process-related emissions is mainly reflected in the different

proportion of alternative raw materials. In terms of substitution rates for raw materials, both production processes show higher substitution rates at smaller production scales. It means that raw material substitution was relatively more common in small scale production. For the two production scales (≤300 t/d and in the range of 500~900 t/d) in the Shaft kiln process, the substitution rates of raw materials are 2.77% and 4.41%, respectively, with corresponding emission reductions of 15.16 kg/t and 15.91 kg/t. For the two production scales (< 2000 t/d and 2000~2500 t/d) in the NSP process, the rates of substitution with raw materials are 2.95% and 3.81%, respectively, with corresponding emission reductions of 8.16 kg/t and 12.59 kg/t. Due to the different in chemical composition of clinker and substitution rate of raw material, the process-related emissions of various scale NSP process are little higher than that of Shaft kilns.

3.2 Analysis of disparity in regional carbon emission factors

As shown in Figure 3(a), the emission factors of cement clinkers tend to increase from the eastern coastal to the western inland regions. The western regions (including Tibet, Xinjiang, Inner Mongolia, and Yunnan) have the highest emission factors, and the eastern regions (including Zhejiang, Jiangsu, Guangxi, and Hebei) have lower emission factors than the central regions (including Shanxi, Henan, Hubei, and Hunan). Hebei and Guangxi have the lowest emission factors, which can be attributed to various factors. Specifically, in Guangxi, the MgO content in clinkers is remarkably lower than the national average level, and in Hebei the substitution rate of raw materials is very high, thus reducing process-related emissions.

Figure 3 Emission factors and composition of regional clinker in 2015

Cao and MgO in clinkers are decomposed from calcium carbonate and magnesium carbonate respectively, which are the main factors affecting the process-related emission. With respect to process-related emissions, the MgO content of clinker samples for the NSP process tends to decrease with increase in CaO content (as shown in Figure 4). In general, the MgO content of the clinkers across China is higher than the standard emission factor specified by the CSI (Gao et al., 2017b). Clinker samples from the NSP process and Shaft kiln have an average MgO content of 2.20% and 2.30%, respectively. In China, the high-MgO regions are mainly distributed in Shandong, Henan, Hebei, Shanxi, Fujian, and Jiangxi. As a result of the high MgO content, Fujian, Jiangxi, and Henan are areas of higher process-related emissions as shown in Figure 3(b). While Hubei, Hunan, Guizhou, and Yunnan are provinces with low MgO content where the process-related emissions are lower than the standard emission factor (525 kg/t) specified by the CSI (2011), as shown in Figure 3(b).

Figure 4 CaO and MgO contents in clinker for the surveyed NSP samples

Note: The first two digits of the sample number are the province number, and the others are the provincial sample number.

Energy intensity is determined by diverse factors, including production processes, production scales, production experience and management level. In China, clinkers from the

northern coast exhibit the highest energy efficiency, followed by those from the southern coast. The northwest and southwest China are characterized by high energy intensity and high fuel-related emissions, as shown in Figure 3(c). The above analysis shows that in China, the fuel intensity (110.04 kgce/t) of the NSP process is lower than that (121.09 kgce/t) of the Shaft kiln process, as described in Table S2. Judging by the relationship between production processes and energy intensity, the energy intensity of clinkers is lower than the national average in those regions (including Hebei, Henan, Liaoning, and Jiangsu) where the proportion of NSP clinker production is higher. It can also be concluded that the application of the NSP process, especially large scale NSP kiln production lines, is beneficial for reducing the energy intensity of clinkers. Regional energy intensity and production scale (> 4000 t/d) showed a high correlation (Figure 5). Among the 22 provinces, energy intensity is relatively low in the regions where production capacity of 4000 t/d accounts for a high overall proportion, whereas energy intensity—and consequently, fuel-related emission factors—are relatively high in the regions (including Guizhou, Tibet, Xinjiang, and Yunnan) where production capacity of 4000 t/d accounts for a low overall proportion, as shown in Figure 3(c). Thus large scale production can reduce energy emission intensity of clinker.

Figure 5 Relationship between regional energy intensity and production scales >4000 t/d

Substitution of steel slag, fly ash, phosphorous slag, or sulfate slag for natural calcium and siliceous materials is the main way to reduce process-related emissions of clinkers. The survey of the 22 provinces shows that the substitution rates of raw material are relatively high

in the regions where steel, phosphorite, and coal resources are widely distributed, including Hebei (a large steel-producing province); phosphorite rich provinces (including Guizhou and Yunnan); and large coal-producing provinces (including Shanxi, Shaanxi, and Shandong), as shown in Figure 3(d). For the Shanxi and Hebei provinces, steel slag and fly ash are used to substitute natural materials such as limestone and sandstone, resulting in emission reductions of 16.89 kg/t and 15.87 kg/t, respectively. Southwest China is also the major region where emission reductions are achieved by raw material substitution. For Guizhou, Yunnan, and Sichuan, the main substitute materials are phosphorous slag, steel slag, and fly ash, which reduce carbon emissions by 24.74 kg/t, 11.83 kg/t, and 10.12 kg/t, respectively. In some large steel-producing and coal-producing provinces (including Jiangsu, Inner Mongolia, and Xinjiang), the rates of substitution of raw materials are presently very low, thereby indicating great potential for the reduction of carbon emissions by raw material substitution in these regions.

4. Selection of methods for regional emission reductions and their potentials

It can be seen from Figure 2 and above analysis that we can use structural adjustment, raw material substitution, and energy saving and fuel substitution to eliminate or reduce the clinker emission factor; these results are slightly different from those established by previous research. The three methods for reduction will be introduced below and basic information relevant to our assessment will be presented.

4.1 Emission reduction potential of structural adjustment

In 2016, China's clinker production capacity was 2.02 billion tons, but the backward production capacity, which is mainly attributed from Shaft kilns and small-scale NSP kilns

(<2000d/t), was approximately 19.46% (393 million tons). Phase out the obsolete production is conducive to capacity reduction, energy conservation, and emission reduction, as the fuel-related emissions and fuel intensity of Shaft kiln are higher than that of NSP kiln, and those of small-scale NSP kilns are higher those that of large-scale NSP kilns (>4000d/t) (Table S2). Thus, this policy was announced in the *Cement industry capacity reduction action plan (2017-2020)*. Qiao Longde, the president of the China Cement Association (CCA), said, As the energy conservation and emission reduction are not up to the reduction standard, in the next ten years, a larger cement production line (⩽2500 t/d) will enter a new round of phase out backward production capacities. Therefore, we expect that the production lines less than 2500 t/d in China will be eliminated by 2030.

The emission reduction method of structural adjustment reveals the different change trends of process-related, fuel-related and power-related emissions in regional clinker production. It results in an increase in process-related missions and weakened the emission reduction obtained from raw material substitution in most provinces (Figure 9). In most provinces, the proportion of raw material substitution in small-scale kilns, especially in kilns with 2000~2500 t/d, is higher than that of large-scale kilns. Just for this main reason result in higher process-related emissions, compared to that of small-scale kilns. Thus, Guizhou presented the highest increased process-related emissions (11.94 kg/t). Expect for Sichuan, Chongqing and Guangdong, structural adjustment increases the process-related emissions in most of the surveyed provinces, compared with the value in 2015.

While, this adjustment decreases fuel- and power-related emissions due to improvement in energy efficiency of large-scale kilns, the fuel and power intensity of the kilns > 5000 t/d is

decreased by 8.90% and 14.57%, respectively, as compared to that kilns with 2000~2500 t/d (Table S2). The reduction in fuel-related emissions from structural adjustment method exceeded 6 kg/t in half of the surveyed provinces, where in the proportion of large-scale kilns was relatively lower or there were a large number of Shaft kilns. Power intensity have reduced in a vast majority of provinces; in particular, these consumptions have reduced by 8.55, 7.44, and 11.89 kWh/t in Shanxi, Inner Mongolia, and Tibet, respectively. Moreover, the large NSP line in China is equipped with a low-temperature waste heat power generation system; therefore, shutting down backward and small production capacities will increase the emission reduction potential of WHPG. In southwest China, such as in Sichuan, Chongqing, and Guizhou, structural adjustments can increase the emission reduction of WHPG by more than 12.53 kg/t; and other provinces were reduced in different degree (Figure 6). Power-related emissions caused by structural adjustment have been decreased in all of the surveyed provinces.

In general, structural adjustments can reduce the clinker emission factor of each provinces. In Tibet, Chongqing, and Sichuan, emission factor reduced more than 30 kg/t, where large scale NSP kilns account for a lower proportion. On the contrary, Zhejiang (1.75 kg/t), Hunan (2.90 kg/t), and Jiangxi (3.47 kg/t) emission reduced less because of the minor difference in the energy efficiencies of different scale production lines in these regions (Figure 6).

Figure 6 Emission reduction of structural adjustment

4.2 Emission reduction potential of energy saving and fuel substitution

Owing to the high energy intensity of the calcination process and significant CO_2 release from the fuel and power consumption, energy saving and low carbon emissions are major concerns in clinker production. A total of 260 energy saving technologies and 27 low carbon technologies have been promoted by the National Development and Reform Commission (NDRC) in the *National Key Energy Conservation and Low Carbon Technologies Promotion Catalog (2017),* as significant opportunities to improve energy efficiency exist in China's cement industry and other industrial sectors. Thirty-two potential energy efficiency technologies, including 12 grinding technologies (R1-R12) and 20 calcination technologies (C1-C20), and fuels substitution (A3) were evaluated for provinces of the future cement industry. The description, fuel and power savings, investment, income, emission reductions, and payback period of each of these measures can be found in Talaei et al. (2019), Gao et al. (2017a), Huang et al. (2016), Madlool et al. (2011), Hasanbeigi et al. (2010b), Hasanbeigi et al. (2010a), and *National key energy saving and low carbon technology promotion catalogue* (NDRC, 2018). According to historical data and the present application of various technologies obtained from our survey, studies of the above mentioned authors, and the NDRC, the future applied share of the energy improvement technologies was estimated according to their unit costs and penetration parameters in the surveyed provinces (Table S3).

The emission reduction of this method is reflected in three aspects: power saving, fuel substitution and fuel efficiency improvement. The fuel intensity, fuel substitution, and power intensity of surveyed provinces were subsequently been estimated. Compared with 2015, the

fuel intensities of all the provinces decreased by more than 10 kgce/t, and Inner Mongolia, Shanxi and Tibet decreased the most, which was 21.63, 20.61, and 20.25 kgce/t respectively. In 2030, the fuel substitution in eastern coastal provinces are relatively higher (>20%), while that in Xinjiang and Tibet are the lowest, 9.18% and 4.69% respectively. This method increases the WHPG and decreases the power consumption in clinker production in all of the investigated provinces. After deducting the WHPG, the power intensity are less than 30 kWh/t in the investigated provinces, expect for Tibet (65.95 kWh/t), Xinjiang (53.78 kWh/t), Shanxi (35.38 kWh/t), and Yunnan (34.05 kWh/t) .

For all the investigated provinces, except Tibet, the emission reduction potential of energy saving and fuel substitution exceeded 70 kg /t (Figure 7). In Tibet, the slow diffusion of energy saving technology and the insufficient availability of alternative fuels result in an emission reduction potential of only 46.34 kg/t (Figure 7). In 2030, the fuel substitution rate of the cement industry in Tibet is predicted to be less than 5%, whereas that of Guangdong, Jiangsu, and Zhejiang is predicted to be close to 30%. In these provinces, the emission reduction potential of fuel substitution is 72.06, 71.53, and 76.58 kg/t, respectively (Figure 7). Due to the diffusion of fuel saving technologies, such as energy management and process control systems, combustion system improvement, and low nitrogen decomposing furnace system, the emission reduction potential of these provinces, such as Shanxi, Jiangxi, Guangdong, and Fujian, is predicted to exceed 40 kg/t in 2030. In provinces with a high proportion of ball milling and the third generation grate cooler, such as Shaanxi, Xinjiang, and Inner Mongolia, the emission reduction potential of power saving is evident, and the emission reduction potential of these regions are 25.29, 12.40, and 17.19 kg/t, respectively

(Figure 7).

Figure 7 Emission reduction of energy saving and fuel substitution

4.3 Emission reduction potential of raw material substitution

Utilizing industrial waste as an alternative material has been proven to be economically and environmentally viable for the cement industry (Carvalho et al., 2017; Darsanasiri et al., 2018; Iacobescu et al., 2011; Iacobescu et al., 2013; Maes and Belie, 2017; Taher, 2007; Xu et al., 2012). With the implementation of China's comprehensive utilization of resources, the substitution of raw materials will become the focus of process-related emission reduction in the future. This study only considers substituting steel slag and phosphorus slag with limestone (A1), fly ash, and copper slag for the sandstone or iron materials (A2) in the surveyed regions because significant amounts of these materials are produced in China. The survey data show significant regional differences in the substitution of raw materials, and that the rates of substituting raw materials are affected by the availability and price of substitute materials and their maximum substitution rate (Dai, 2017; Iacobescu et al., 2011; Uson et al., 2013). The studies by Iacobescu et al. (2013), Feng and Li (2010), and Rao (2011) indicate that the amount of steel slag mixed in cement raw materials can reach 10%. The addition of phosphorus slag is mainly affected by P_2O_5 in the clinker. When the content of P_2O_5 in clinker exceeds 0.5%, the compressive strength decreases rapidly (Li and Zhai, 2011). Thus, the optimal concentration of phosphorus slag to be added to the raw meal is 6–10% (Yang et al., 1995). Due to this restriction on the maximum addition amount, the substitution rate of

raw materials is obtained via a questionnaire rather than the popularity rate of low-carbon technology. The possible alternative rate of the surveyed province was calculated based on the availability of the technical, economic, and alternative raw material, according to the questionnaire of production technicians, managers of cement plant, and staff of CCA.

In the areas with a high proportion of steel slag output to clinker output, such as Hebei, Jiangsu, Liaoning, and Shanxi, the calcium and silica substitution ratios obtained from the questionnaire was relatively high, ranging from 6.21–11.13% and 6.41–10.93% (Table S1), respectively in 2030. The emission reduction of raw material substitution in these provinces is 86.12, 56.23, 59.66, and 59.73 kg/t, respectively. Furthermore, in Hubei, Guizhou, Sichuan, and Yunnan, which have higher phosphorus slag production, the replacement ratios of calcium and silicon raw materials was in the range of 5.46–7.71% and 4.69–7.71% (Table S1), respectively, and their emission reductions are 61.66, 45.16, 52.68, and 46.66 kg/t (Figure 8), respectively. Additionally, other central and eastern provinces yield a lower emission reduction potential due to the constraints of alternative raw materials. This combined with the long transportation distance and high production cost in Xinjiang, Tibet, and other northwest regions, results in a lower raw material substitution rate and reduction potential in these regions (Figure 8).

Figure 8 Emission reduction of raw material substitution

4.4 Regional Emission Reductions Potential

Regional clinker emission factors in 2030 were calculated based on the assumption and

surveyed data of the three emission reduction methods. Figure 9 shows the provincial changes in emission factors for the clinker production. From 2015 to 2030, emissions reduction for all investigated provinces exceed 100 kg/t (Tibet has the lowest reduction potential of 101.41 kg/t). Especially in Jiangsu, Hebei, Sichuan, and Guangdong with the emission reduction potential of 174.60, 169.25, 165.82, and 162.05 kg/t, corresponding to a reduction of 20.58%, 20.16%, 18.91%, and 18.99% respectively. The emission factor in north coast, east coast, and southwest experience the greatest reduction, which is driven by a combination of the use of raw materials and fuel substitution. The national average emission factor estimated in 2030 is 715.33 kg/t, a decline of 16.65% compared to that in 2015. The emissions reduction estimated by Wei et al. (2019) over the period 2018-2030 (158.50 kg/t) were higher than those in the present study (142.85 kg/t), as a higher diffusion rate of raw material (~21%) and fuel substitution (~42%) in 2030 was used. In 2030, the clinker emission factors of the 13 surveyed provinces were higher than the national average level. These provinces are mainly located in northwest, and middle reaches of the Yellow River and the Yangtze River, and Tibet has the highest emission factor of 858.14 kg/t (Figure 9(d)). The remaining 9 provinces have lower clinker emission factors, and they are mainly distributed in east and north coast. In particular, Hebei has the lowest emission factor of only 670.34 kg/t; raw material and fuel substitution each are responsible for over 40% of its total reduction (Figure 9).

Across all the investigated provinces, the energy saving and fuel substitution account for approximately 65.98% of the overall reduction in carbon intensity; the remaining two methods contribute about 25.72% and 8.30% each. Structural adjustment has the minimum

proportion because only three provinces (Tibet, Chongqing, and Sichuan) have an emission reduction potential of more than 30 kg/t (Figure 9(a)). Emission reductions via improvement in energy saving and fuel substitution are mainly concentrated in Zhejiang, Fujian, Jiangxi, Anhui, Henan, Hunan, Guangdong, Guangxi, and Shaanxi (Figure 9(b)), which account for over 70% of the total reduction in these provinces, and over 45% in the other provinces. Contribution of the emission reduction can differ from place to place. The emission reductions of this method in Inner Mongolia, Shaanxi, Xinjiang, and Tibet are mainly realized via energy saving technologies, while fuel substitution contributes to most of the method reductions in Guangdong, Guangxi, Jiangsu, and Zhejiang. China's major iron and steel producing provinces as well as large phosphorus chemical provinces lead to the high amounts of raw material substitution reduction. Hebei has the largest raw material substitution reduction of 73.20 kg/t (Figure 9(c)), which contributes approximately 43.25% of the total reduction in the region. Five provinces mainly located in northwest China have raw material substitution reduction of less than 30 kg/t, of which Tibet has the smallest reduction of 15.83 kg/t (Figure 9(c)).

Figure 9 Clinker emission factor and emission reduction among provinces by 2030

In terms of emission composition, fuel-related emissions are the major factor contributing to emission factor reduction, followed by process-related emissions and power-related emissions, which reduce by 93.38, 35.14, and 14.34 kg/t, accounting for

65.37%, 24.60% and 10.04% respectively. Jiangsu, Zhejiang, Shandong, Guangdong, and Guangxi have great potential (more than 100 kg/t) for fuel-related emissions. Process-related emission reduction can be mainly attributed to the substitution of raw materials, while shut down backward production facilities contribute a small increase in process-related emission, especially in Guizhou, Hunan, Shandong, and Henan, where the raw material substitution rate of Shaft kiln and small-scale NSP kilns is higher than that of large-scale NSP kilns. And, the provinces, such as Zhejiang, Anhui, Fujian, and Guangxi, have the lowest power-related emissions reduction (7.32-8.57 kg/t), due to the high efficiency of power at current stage.

The combined standard uncertainty and expanded uncertainty of our estimate for the emission factor in the provinces are calculated by adopting the methodologies (JCGM, 2010). The combined standard uncertainty of the national clinker emission factor is 30.04, and its relative expanded uncertainties were within the range of 7.64-11.45%. The uncertainties of process-related, fuel-related, and power-related emissions are also estimated at 0.96-1.45%, 5.67-8.51%, and 7.63-11.44%, respectively. The uncertainty of emissions factor from Tibet is the smallest (4.54-6.81%), while the uncertainty for Jiangsu, having the lowest emission factor, is the largest (9.27-13.90%), due to alternative fuel use, which is estimated to contribute more to the variance of emissions.

5. Conclusions

As the second largest CO_2 emitter, China's cement industry has attracted much attention in its emissions. However, the status and reduction potential of clinker emission factors at the provincial level were not fully studied. Based on the survey production data, application of

energy saving technologies and emissions reduction policy of China's cement industry obtained from the research project, a remarkable disparity in carbon intensity across different production process and scales and regions was noted; and future emission factors from the province's cement industry were forecasted while taking structural adjustment, raw material substitution, and energy saving and fuel substitution into account. The main conclusions that can be drawn from the present study are summarized as follows:

(a) The emission factor of the Shaft kiln process is higher than that of the NSP process; for the two processes, the emission factor of small-scale production lines is higher than that of large-scale production lines. This discrepancy is mainly determined by the fuel and power intensity.

(b) Regional distribution shows that the emission factors of clinker tend to increase from the eastern coast to the western inland regions. Fujian, Jiangxi, and Henan are areas of higher process-related emissions; fuel-related emission are relatively high in Guizhou, Tibet, Xinjiang, and Yunnan.

(c) Structural adjustment leads to the different change trends of process-related , fuel -related and power-related emissions in regional clinker production. It increases the process-related emissions in most of the surveyed provinces, while decreases the fuel-related and power-related emissions of each provinces.

(d) Energy saving and fuel substitution is the major method contributing to emission factor reduction. Fuel-related emission reduction in surveyed provinces mainly comes from fuel substitution or energy saving technologies. Power saving technologies makes the power-related emissions reduced in different degree in the investigated provinces.

(e) We estimated the national average emission factor in 2030 to be 715.33 kg/t, indicating a decline of 16.65% compared with that in 2015, in which the fuel-related, process-related, and power-related emissions reduced by 93.38, 35.14, and 14.34 kg/t, respectively.

The conclusions from these studies, not only gave a comprehensive understanding of regional distribution of clinker emission factors in China, but also show us a clearer picture of the reduction potential of the three methods in the surveyed provinces. These results can be effectively applied to evaluate the relative effectiveness of each emission reduction measure and provide reference for making policies in reaching energy-saving and emission-reducing objectives.

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Ethics approval and consent to participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Tianming Gao: Conceptualization, Writing draft preparation, Funding acquisition

Lei Shen: Software, Visualization

Jianan Zhao: Methodology, Supervision

Limao Wang: Investigation, Formal analysis

Litao Liu: Investigation, Data curation

Tao Dai: Reviewing and Editing

All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

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Figures

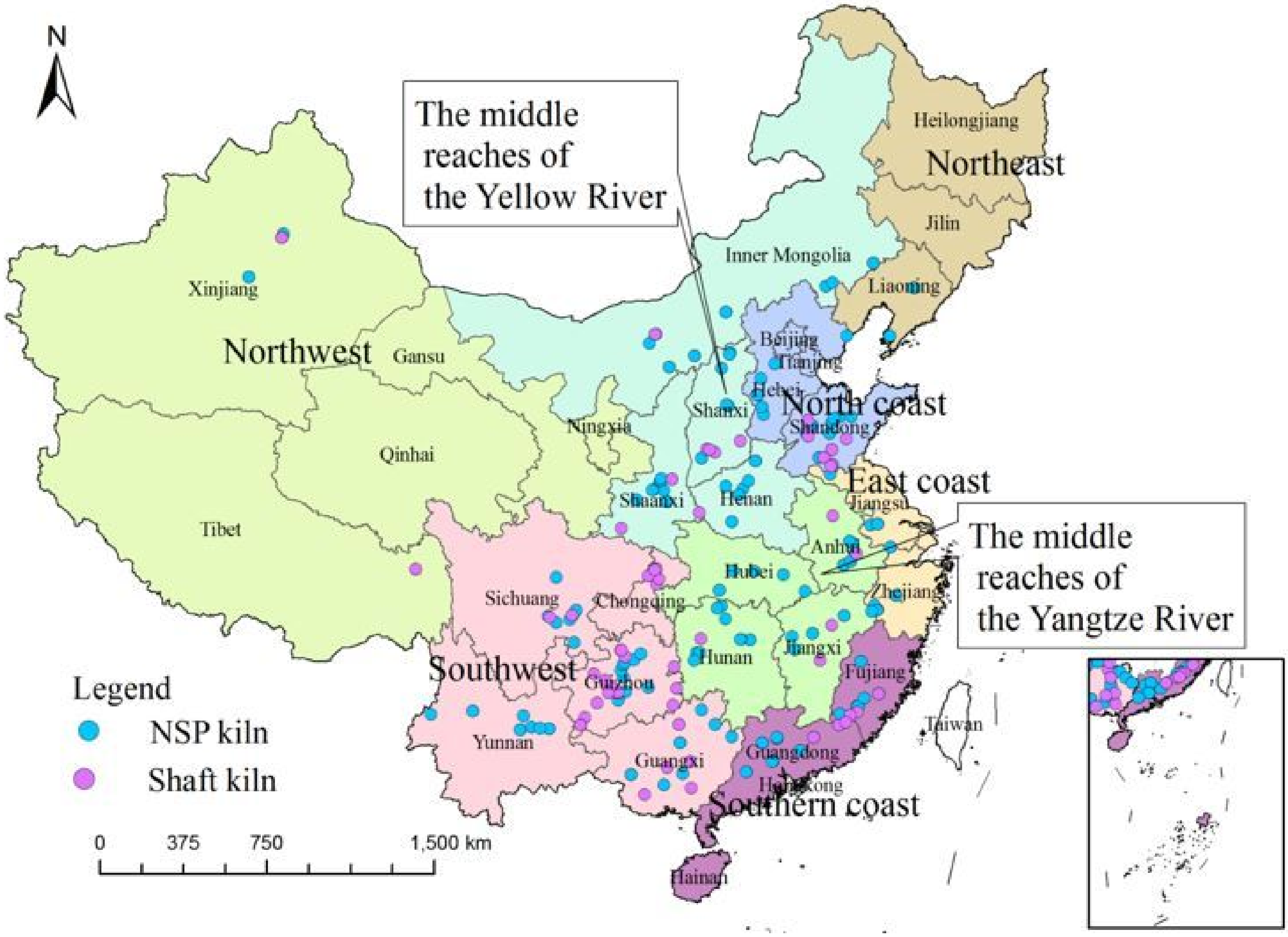

Figure 1

Distribution of the surveyed cement production lines. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

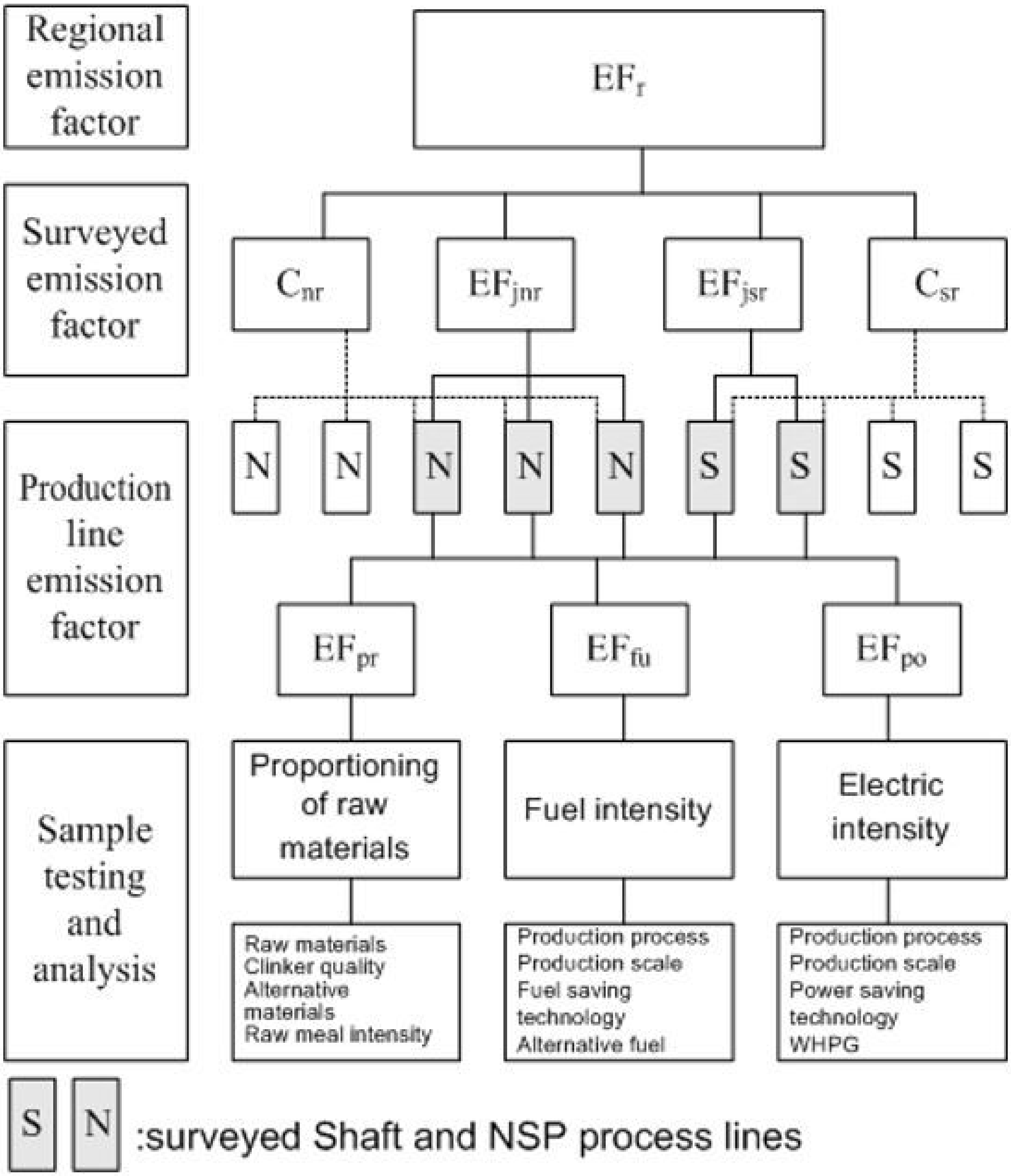

Figure 2

The framework of three tiers regional emission integrated system

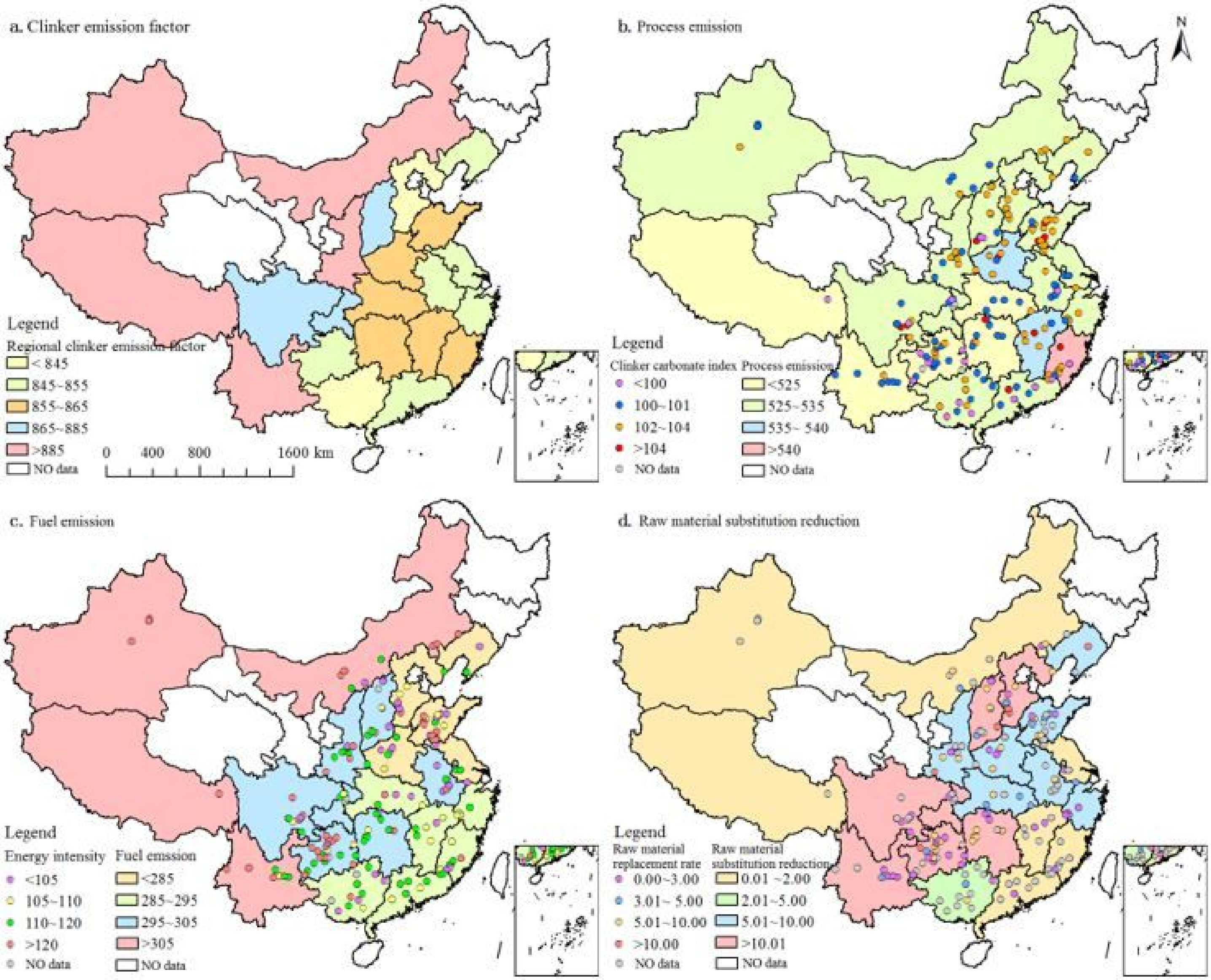

Figure 3

Emission factors and composition of regional clinker in 2015. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

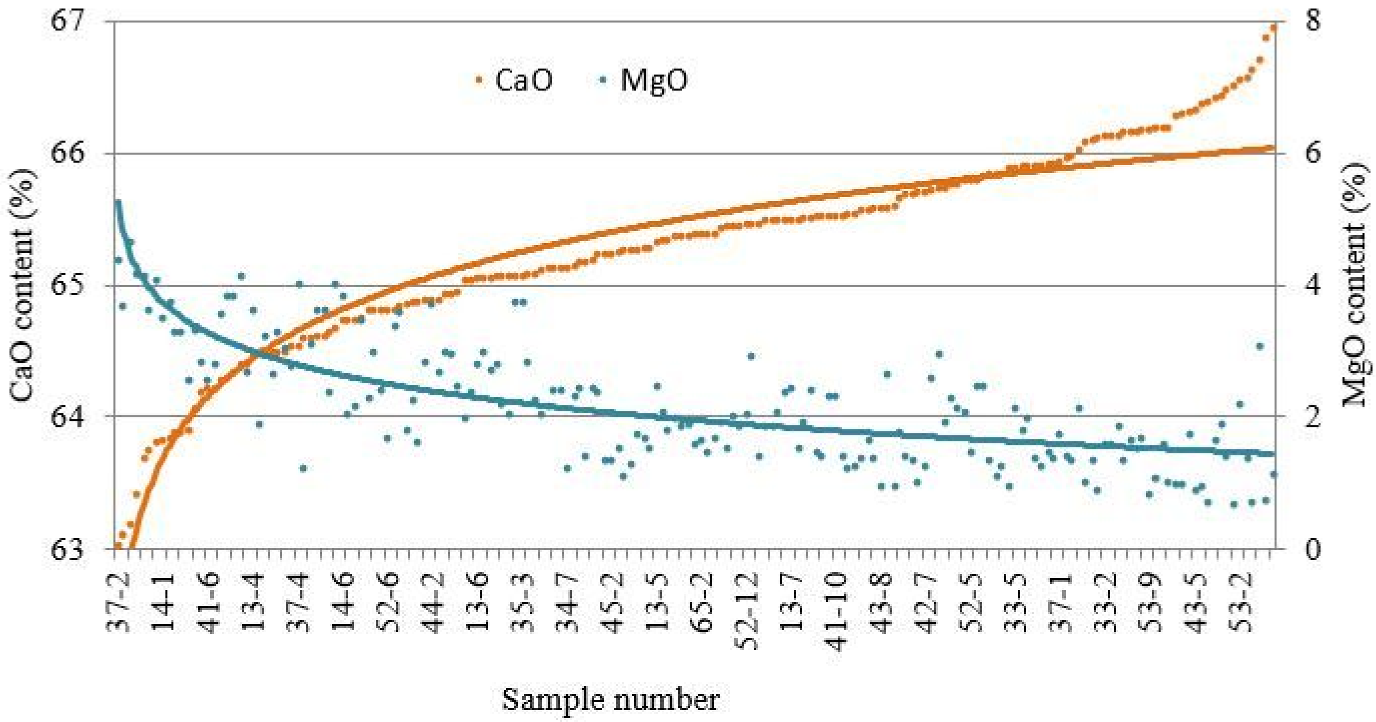

Figure 4

CaO and MgO contents in clinker for the surveyed NSP samples Note: The first two digits of the sample number are the province number, and the others are the provincial sample number.

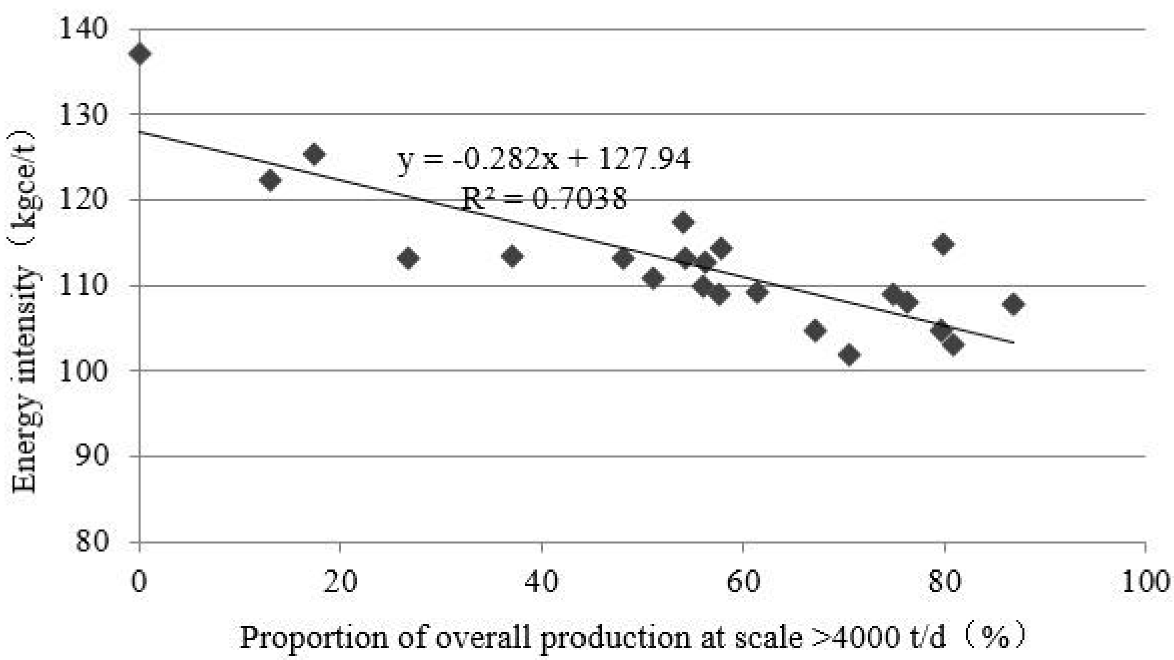

Figure 5

Relationship between regional energy intensity and production scales >4000 t/d

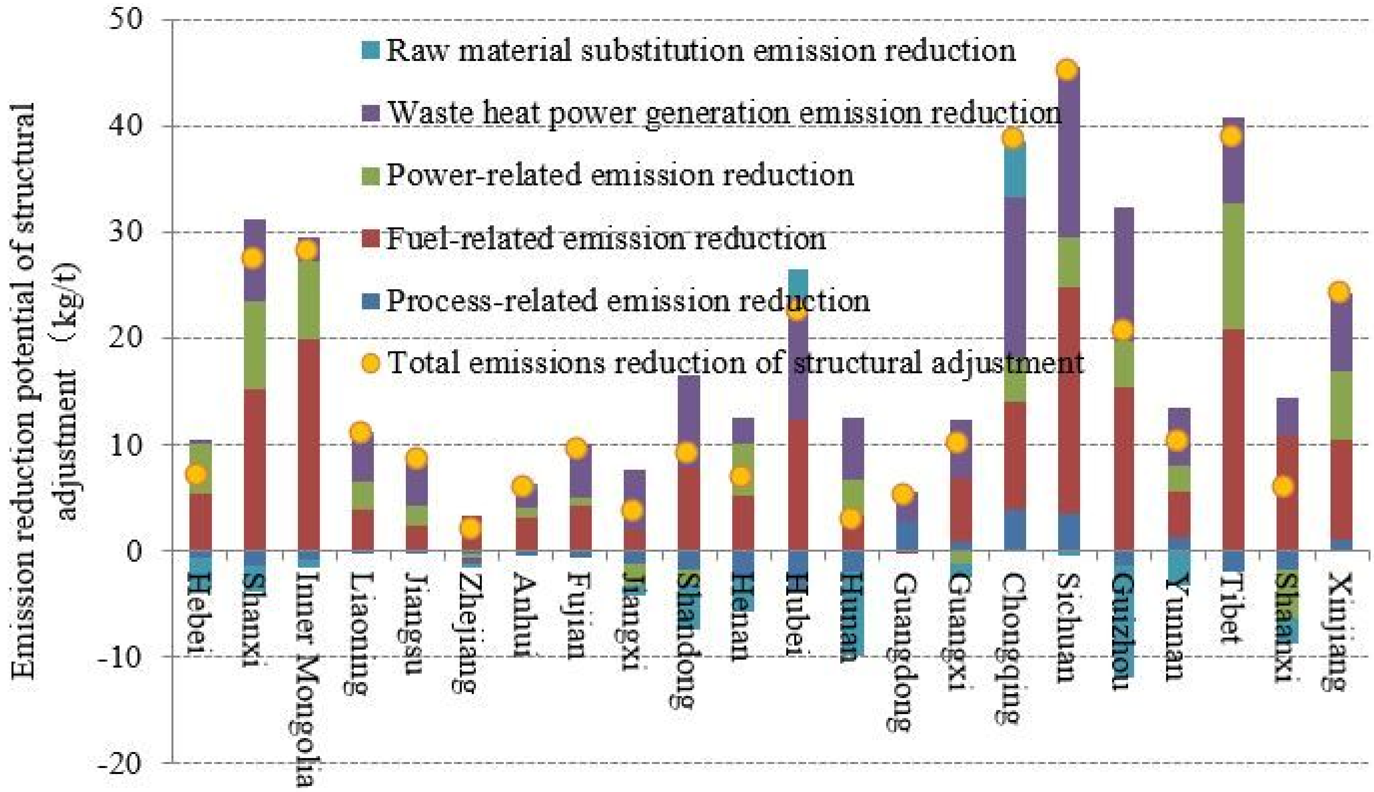

Figure 6

Emission reduction of structural adjustment

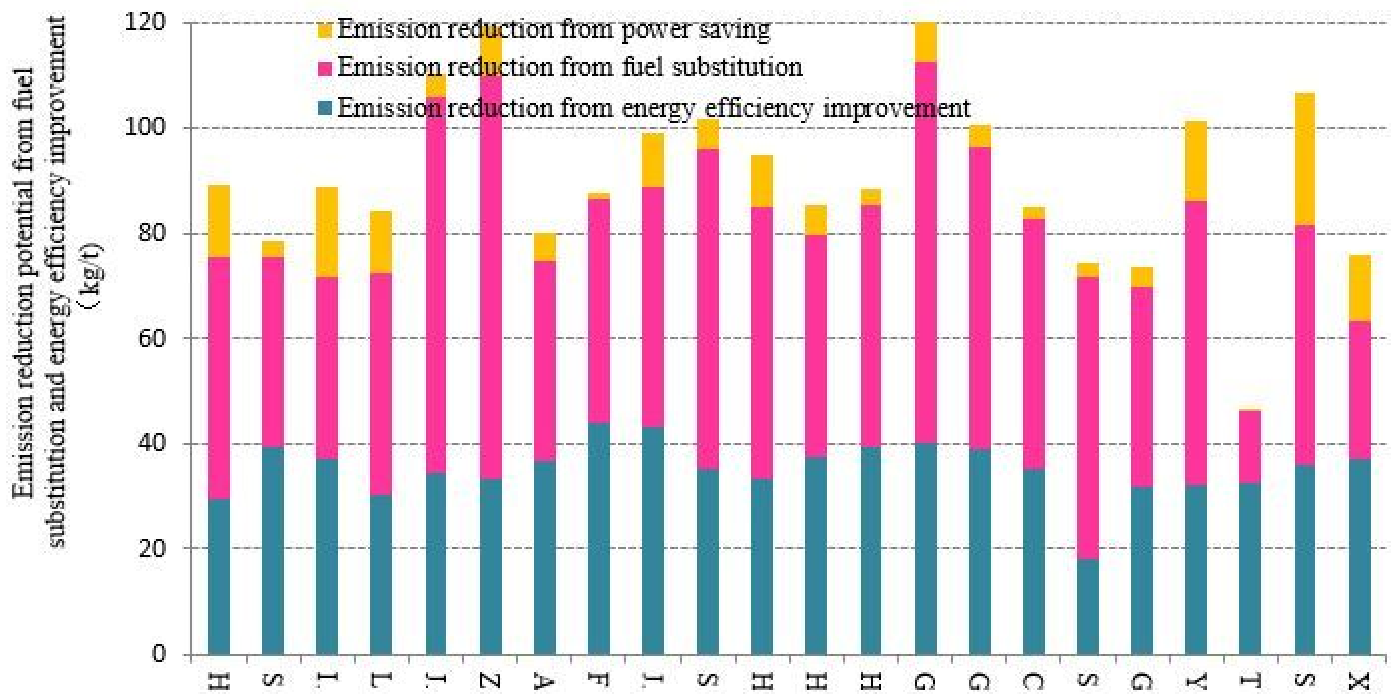

Figure 7

Emission reduction of energy saving and fuel substitution

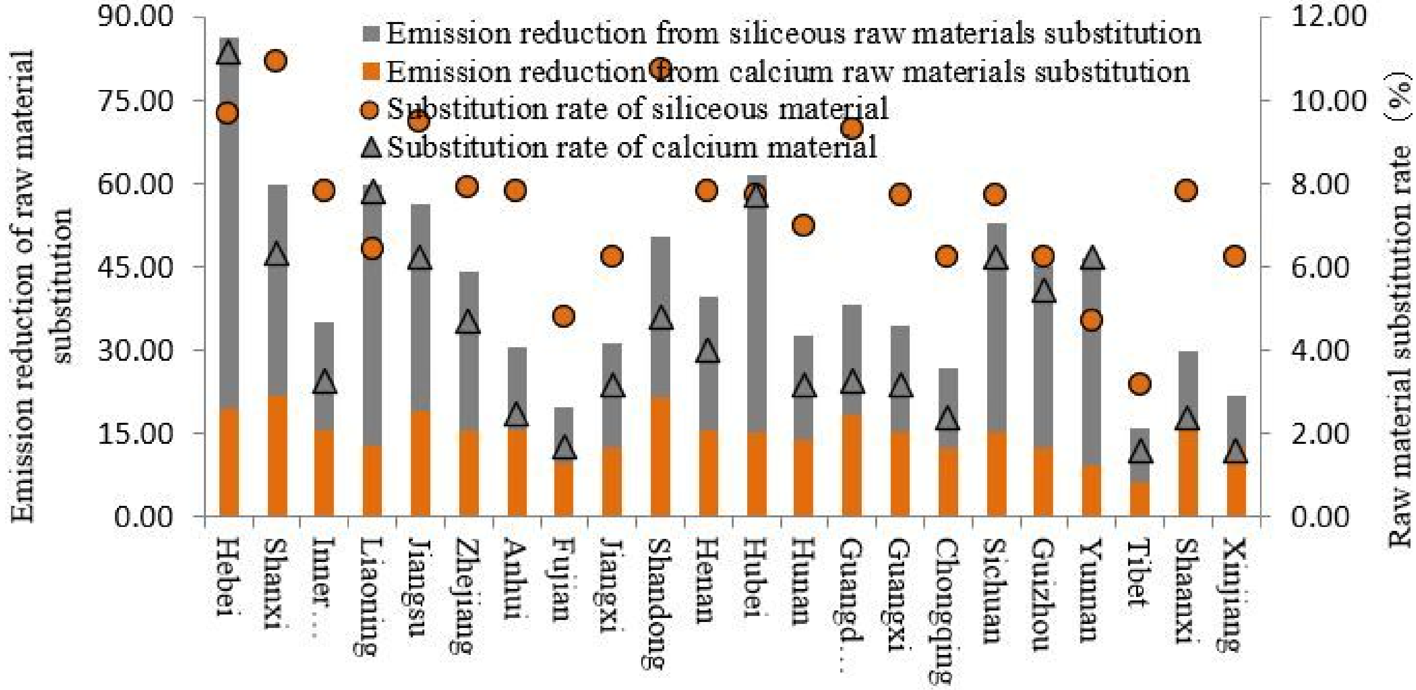

Figure 8

Emission reduction of raw material substitution

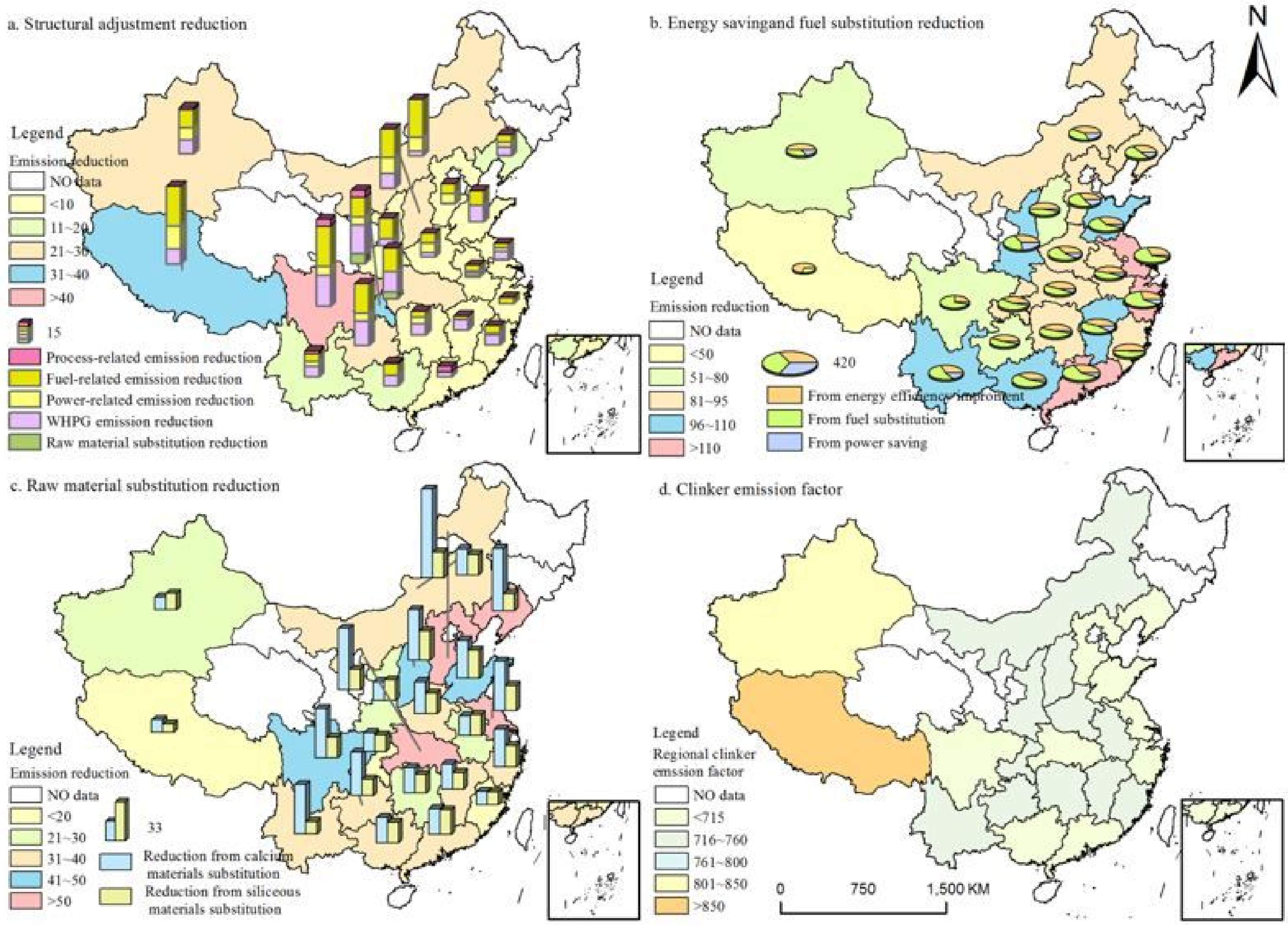

Figure 9

Clinker emission factor and emission reduction potential among provinces by 2030. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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