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作者姓名：王畅、郭越

作者单位：中国海洋大学

作者学历：本科

指导教师：邵帅（上海财经大学）

# Inequality and polarization in energy intensity within China

Chang Wang, Yue Guo

School of Economics, Ocean University of China, Qingdao 266100, China

**Abstract:** As energy saving and emission reduction become a global action, inequality in energy intensity between different regions is a new rising problem that stems a country's energy-saving potential and may lead to social instability. Here, we collect China's provincial panel data (1995-2016) of primary and final energy consumption to evaluate China's inequality and polarization in energy intensity, decompose the inequality index into contributing components, and study possible driving factors behind the inequality pattern both regionally and structurally. The results show that China's inter-province inequality in energy intensity increases, and is exacerbated by the enlarging disparities in energy intensity between the least-developed and most-developed regions of China. The causes for this phenomenon are: (i) rather loose regulatory measures on mitigating coal consumption; (ii) increasing inter-regional energy fluxes embodied in trade; (iii) separate jurisdictions at provincial administrative levels. These factors can synthetically result in unintended spillover to areas with inferior green technology, suggesting an increasingly uneven distribution of raw-material intensive industries and higher national total emissions. The results reveal the necessities of regional coordination and cooperation to achieve a green economy.

**Key words:** Inequality, Polarization, Energy intensity in China, Zenga inequality index

## 1. Introduction

Although there exist different opinions, energy intensity is one of the indicators most commonly used for evaluating the efficiency of comprehensive energy utilization in a country (region) and reflects the resource and environmental costs of economic development [1-3]. With the rapid growth of China's energy consumption, the contradiction between energy demand and environmental problems has become increasingly prominent, which has made improving energy efficiency a top priority [4]. To resolve this contradiction, China has launched a series of regulations that proposed significant goals for future energy intensity [5], such as the Energy Development Strategic Action Plan, the U.S.-China Joint Presidential Statement on Climate Change, Made in China 2025 and "Five-Year Plan" (FYP). Effective progress has been made toward achieving these targets: according to the IEA's report *Energy Efficiency 2018*, the worldwide movement of economic activities away from energy-intensive industrial sectors has offset more than a 25% increase in final energy use, 40% of which was due to China's contribution [6].

While setting significant energy-saving targets for the whole country, China also allocated different energy-saving quotas in different provinces, which resulted in an increasing inequality in energy intensity. Under the 12th “Five Year Plan” (a series of social and economic development initiatives implemented during 2010-2014), the regional allocation of energy intensity is based on the “common but differentiated” burden sharing rules [7] and is quite diverse among provinces according to their economic development levels [8-9]: Xinjiang, Xizang and Qinghai, some of the least developed and least energy-saving provinces in China, are required to cut their energy intensity by 10%, while Tianjin, Shanghai, Jiangsu, Zhejiang and Guangdong, some of the most developed and most energy-saving provinces, are required to cut their energy intensity by 18%. Since energy intensity targets are not allocated equally across regions, they may have triggered traditional manufacturing transfer and amplified the energy intensity gap between different regions. However, this disparity in China’s energy intensity does not receive enough attention. Primary energy intensity inequality may hinder the achievement of a country's energy intensity target [10], given that some regions’ energy-saving potential is not fully exploited through technological spillovers and inter-regional cooperation [11-13]. Moreover, energy intensity inequality reflects unequal living standards across Chinese households [14-15] and may lead to social instability [16].

Therefore, an improved understanding of inequality is a prerequisite for an effective policy for energy saving and emission reduction [17]. To better address the problem of inequality in energy intensity, we first characterize China's inequality in energy intensity by adopting provincial annual data from the China Energy Statistical Yearbook (1995-2016) and the Zenga index method, to decompose the driving factors for inequality in energy intensity in terms of provinces, regions, energy transformation and energy consumption structure. The results provide in-depth insights into the present situation, potential causes, and future evolution of inequality and polarization in energy intensity in China. Finally, we conclude that the ongoing regional development plans should be integrated with energy conservation goals and involve the development of renewable energy and green technology.

# 2. Method and data

## 2.1. Measuring China’s interprovincial energy intensity inequality

We adopt the Zenga index [18] to calculate China’s inter-provincial inequality in primary and final energy intensities, which can measure inequality at various points of the distribution and reflect specific province’s contribution to the overall inequality. The primary energy intensity of province $h$ can be decomposed to the product of the energy transformation rate (defined as the quotient of primary energy consumption and final energy consumption) and final energy intensity as follows:

$$p_h = \frac{PE_h}{GDP_h} = \frac{PE_h}{FE_h} \cdot \frac{FE_h}{GDP_h} = t_h \cdot f_h \tag{2-1}$$

where $p_h$, $t_h$, and $f_h$ are the primary energy intensity, energy transformation rate and final energy intensity of province h, respectively; $PE_h$, $FE_h$, and $GDP_h$ are primary energy consumption, final energy consumption, and gross domestic product of province h, respectively. Mathematically, the Zenga index is based on the weighted ratio of the upper and lower arithmetic means. Thus, we sort the primary energy intensity $p_h$ in ascending order and set the province with the highest primary energy intensity as province $r$, and the upper and lower arithmetic means of the primary energy intensities can be calculated as follows, respectively:

$$M_h^-(p) = \frac{\sum_{j=1}^{h} PE_j}{\sum_{j=1}^{h} GDP_j} = \frac{\sum_{j=1}^{h} PE_j}{\sum_{j=1}^{h} FE_j} \cdot \frac{\sum_{j=1}^{h} FE_j}{\sum_{j=1}^{h} GDP_j} = M_h^-(t) M_h^-(f) \tag{2-2}$$

$$M_h^+(p) = \begin{cases} \dfrac{\sum_{j=h+1}^{r} PE_j}{\sum_{j=h+1}^{r} GDP_j} = \dfrac{\sum_{j=h+1}^{r} PE_j}{\sum_{j=h+1}^{r} FE_j} \cdot \dfrac{\sum_{j=h+1}^{r} FE_j}{\sum_{j=h+1}^{r} GDP_j} = M_h^+(t) M_h^+(f), h \le r-1 \\ \dfrac{PE_r}{GDP_r} = \dfrac{PE_r}{FE_r} \cdot \dfrac{FE_r}{GDP_r} = M_r^+(t) M_r^+(f), h = r \end{cases} \tag{2-3}$$

where $M_h^-(p)$, $M_h^-(t)$ and $M_h^-(f)$ are the average primary energy intensity, energy transformation rate and final energy intensity of provinces with primary energy intensities less than or equal to $p_h$, respectively; $M_h^+(p)$, $M_h^+(t)$ and $M_h^+(f)$ are the average primary energy intensity, energy transformation rate and final energy intensity of provinces with primary energy intensities higher than $p_h$, respectively. Specifically, since province *r* is the province with the highest primary energy intensity, $M_r^+(t)$ and $M_r^+(f)$ are equal to energy transformation rate and final energy intensity of province *r*, respectively. The primary energy intensity inequality at each point of the distribution can be evaluated by the relative gap between the higher arithmetic mean of primary energy intensity $M_h^+(p)$ and lower arithmetic mean of primary energy intensity $M_h^-(p)$ as follows:

$$I_h(p)=\frac{M_h^+(p)-M_h^-(p)}{M_h^+(p)}=\frac{M_h^+(t)M_h^+(f)-M_h^-(t)M_h^-(f)}{M_h^+(p)}$$
$$=\frac{[M_h^+(t)-M_h^-(t)]\cdot M_h^-(f)}{M_h^+(p)}+\frac{[M_h^+(f)-M_h^-(f)]\cdot M_h^-(t)}{M_h^+(p)}$$
$$+\frac{[M_h^+(t)-M_h^-(t)]\cdot[M_h^+(f)-M_h^-(f)]}{M_h^+(p)}=I_h^t(p)+I_h^f(p)+I_h^{\mathrm{int}}(p) \tag{2-4}$$

where $I_h(p)$ is the relative gap in primary energy intensity between the bottom $h$ provinces and the top $r-h$ provinces. It can be decomposed into the disparity in final energy intensity, the disparity in energy transformation rate and their cross-multiplication term, denoted as $I_h^t(p)$, $I_h^f(p)$ and $I_h^{\mathrm{int}}(p)$, respectively. The overall inequality in primary energy intensity, and its driving factors from the overall relative disparity in energy transformation rate, the overall relative disparity in final energy intensity and the interaction between energy transformation rate and final energy intensity are the means of $I_h(p)$, $I_h^t(p)$, $I_h^f(p)$ and $I_h^{\mathrm{int}}(p)$ weighted by GDP as follows, respectively:

$$I(p)=\sum_{h=1}^{r} I_h(p)\cdot\frac{GDP_h}{\sum_{h=1}^{r} GDP_h} \tag{2-5}$$

$$I^t(p)=\sum_{h=1}^{r} I_h^t(p)\cdot\frac{GDP_h}{\sum_{h=1}^{r} GDP_h} \tag{2-6}$$

$$I^f(p)=\sum_{h=1}^{r} I_h^f(p)\cdot\frac{GDP_h}{\sum_{h=1}^{r} GDP_h} \tag{2-7}$$

$$I^{\mathrm{int}}(p)=\sum_{h=1}^{r} I_h^{\mathrm{int}}(p)\cdot\frac{GDP_h}{\sum_{h=1}^{r} GDP_h} \tag{2-8}$$

## 2.2. Measuring drivers of inequality in energy intensity

Industrial structure, investment ratio, income, urbanization, industrial and export structures, government expenditure and foreign versus indigenous innovation may all be the driving forces of energy intensity fluctuations [19-26]. Based on our knowledge that the energy consumption structures and corresponding mitigating efforts vary among China's provinces, here, we mainly identify the influence of final energy consumption structure on the inequality in final energy intensity. First, we sort final energy intensity $f_h$ in ascending orders and transform final energy intensity into the sum of final energy consumption proportion multiplying final energy intensity:

$$f_h = \frac{FE_h}{GDP_h} = \frac{\sum_{i=1}^{m} FE_{ih}}{FE_h} \cdot \frac{FE_h}{GDP_h} = \sum_{i=1}^{m} s_{ih} \cdot f_h \tag{2-9}$$

where $s_{ih}$ is the final energy consumption proportion of energy $i$ in province $h$ ($r$ provinces and $m$ energy sources in total), and $FE_{ih}$ is the final energy consumption of energy $i$ in province $h$. Similarly, let $M_h^-(s_i)$ and $M_h^+(s_i)$ denote the lower and higher arithmetic average final energy consumption proportions of energy $i$ in province $h$, respectively, and thus we have:

$$M_h^-(s_i) = \frac{\sum_{j=1}^{h} FE_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{h} FE_{ij}} \tag{2-10}$$

$$M_h^+(s_i) = \begin{cases} \dfrac{\sum_{j=h+1}^{r} FE_{ij}}{\sum_{i=1}^{m}\sum_{j=h+1}^{r} FE_{ij}}, h \le r-1 \\ \dfrac{FE_{ir}}{\sum_{i=1}^{m} FE_{ir}}, h = r \end{cases} \tag{2-11}$$

Similarly, we define $M_h^-(f)$ and $M_h^+(f)$ as the lower and higher arithmetic means of final energy intensity and decomposed them as follows, respectively:

$$M_h^-(f) = \sum_{i=1}^{m} M_h^-(s_i) \times M_h^-(f) \tag{2-12}$$

$$M_h^+(f) = \sum_{i=1}^{m} M_h^+(s_i) \times M_h^+(f) \tag{2-13}$$

Therefore, $I_h(f)$, the inequality in final energy intensity of province $h$ can be decomposed into the disparity in final energy consumption structure, the disparity in final energy intensity and their cross-multiplication term as follows:

$$
\begin{aligned}
I_h(f) &= \frac{M_h^+(f)-M_h^-(f)}{M_h^+(f)} \\
&= \sum_{i=1}^{m} \frac{[M_h^+(s_i)-M_h^-(s_i)]\times M_h^-(f)}{M_h^+(f)} \\
&+ \sum_{i=1}^{m} \frac{[M_h^+(f)-M_h^-(f)]\times M_h^-(s_i)}{M_h^+(f)} \\
&+ \sum_{i=1}^{m} \frac{[M_h^+(s_i)-M_h^-(s_i)][M_h^+(f)-M_h^-(f)]}{M_h^+(f)} \\
&= \sum_{i=1}^{m} I_h^{s_i}(f) + I_h(f) + \sum_{i=1}^{m} I_h^{\mathrm{int}_i}(f)
\end{aligned}
\tag{2-14}
$$

where $I_h^{s_i}(f)$, $I_h(f)$ and $I_h^{\mathrm{int}_i}(f)$ are the contributions of inequality in final energy intensity from the consumption proportion of energy $i$, final energy intensity and their cross-multiplication term in province *h*, respectively. Similarly to Equations (5)-(8), the overall contribution to final energy intensity from the consumption proportion of energy *i*, final energy intensity and the interaction between them are the means of $I_h^{s_i}(f)$, $I_h(f)$ and $I_h^{\mathrm{int}_i}(f)$ weighted by GDP. Their calculation formulas are not shown due to the limited space.

## 2.3. Decomposing into within-group and between-group components and evaluating polarization

The Zenga index has the high quality of additive decomposability [27] and can be decomposed into the sum of the within-group inequality and the between-group inequality without redundant terms. Here, we divide $r$ provinces in China into $k$ subgroups and set their GDP and primary energy intensity as $y_1, y_2, ...., y_r$ and $p_1, p_2, ...., p_r$, respectively. In addition, $n_{hg}$ denotes the GDP of province $h$ if province $h$ is within subgroup $g$ as follows:

$$
n_{hg} = \begin{cases} y_h, & if \quad province \;\; h \;\; is \;\; included \;\; in \;\; subgroup \;\; g \\ 0, & if \quad province \;\; h \;\; is \;\; not \;\; included \;\; in \;\; subgroup \;\; g \end{cases}
\tag{2-15}
$$

The data structure is shown in Table 2-1.

**Table 2-1| Data structure of primary energy intensity of $k$ subgroups**

| | Subgroups | | | | | Total |
|---|---|---|---|---|---|---|
| | **1** | **...** | $g$ | **...** | $k$ | |
| $p_1$ | $n_{11}$ | ... | $n_{1g}$ | ... | $n_{1k}$ | $n_{1\bullet}$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $p_h$ | $n_{h1}$ | ... | $n_{hg}$ | ... | $n_{hk}$ | $n_{h\bullet}$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $p_r$ | $n_{r1}$ | ... | $n_{rg}$ | ... | $n_{rk}$ | $n_{r\bullet}$ |

**Note:** Primary energy intensity $p_h$ is sorted in ascending order.

Thus, we have:

$$\sum_{g=1}^{k} n_{\bullet g} = N \tag{2-16}$$

$$\sum_{h=1}^{r} n_{hg} = n_{\bullet g} \tag{2-17}$$

$$\sum_{g=1}^{k} n_{hg} = n_{h\bullet} \tag{2-18}$$

The Zenga index for inequality in primary energy consumption intensity can be decomposed into within-group component $I^w(p)$ and between-group component $I^b(p)$ as follows:

$$I(p) = I^w(p) + I^b(p) \tag{2-19}$$

$$I^w(p) = \sum_{l=1}^{k}\left\{\sum_{h=1}^{r}\left[\frac{M_{hl}^{+}(p) - M_{hl}^{-}(p)}{M_{h\bullet}^{+}(p)}\right] b(l|h) u(l|h) \frac{n_{h\bullet}}{N}\right\} \tag{2-20}$$

$$I^b(p) = \sum_{l=1}^{k}\sum_{g:g\neq l}\left\{\sum_{h=1}^{r}\left[\frac{M_{hg}^{+}(p) - M_{hl}^{-}(p)}{M_{h\bullet}^{+}(p)}\right] b(l|h) u(g|h) \frac{n_{h\bullet}}{N}\right\} \tag{2-21}$$

In these equations, $M_{hl}^{+}(p)$ and $M_{hl}^{-}(p)$ are higher and lower average primary energy intensities for subgroup $l$, respectively, and $M_{h\bullet}^{+}(p)$ is the higher average energy intensity in all subgroups. Variable $b\left(l\middle|h\right)=P_{hl}/P_{h\bullet}$ represents relative GDP of subgroup $l$ to all subgroups with lower energy intensities than $p_h$, where $P_{hl}$ denotes summed GDP for provinces with energy intensities lower than or equal to $p_h$ in subgroup $l$, and $P_{h\bullet}$ stands for summed GDP for provinces with energy intensities less than or equal to $p_h$ in all subgroups. Variable $u(l|h)$ represents relative GDP of subgroup $l$ to all subgroups with higher energy intensities. When $h=r$, $u(l|h)=n_{rl}/n_{r\bullet}$; when $h=1,2,...,r-1$, $u(l|h)=\left(n_{\bullet l}-P_{hl}\right)/\left(n-P_{h\bullet}\right)$.

The magnitude of polarization reveals the convergence of energy intensity within each exogenous grouped region and divergence of primary energy intensity between various exogenous grouped regions. The polarization index can be measured by the comparison between within-group component $I^{w}(p)$ and between-group component $I^{b}(p)$. According to Zhang & Kanbur (2001), we adopt the Z-K index to construct the energy intensity polarization index as follows:

$$Z-K=\frac{I^{b}(p)}{I^{w}(p)} \tag{2-22}$$

The Z-K index being greater than 1 indicates a strong multi-polarization of the tested sample.

## 2.4. Data source and manipulations

The data collected initially in this study concerns the provincial energy consumption (physical units), which are from provincial energy balance sheets in the *China Energy Statistical Yearbook* (1996-2017). We convert these data into coal equivalent using conversion factors (see Supplementary Table 1) from the yearbook.

# 3. Analysis results and discussion

## 3.1. Evolution of inequality in energy intensity

Here, we evaluate the inter-provincial inequality in primary energy intensity adopting the Zenga index and decompose it into three components: the inequality in final energy intensity, the inequality in energy transformation rate, and the interaction between disparities in final energy intensity and energy transformation rate. The inequality in primary energy intensity inequality and its decomposition, along with the temporal evolution of energy intensity, are depicted in Fig. 3-1.

Fig. 3-1 clearly demonstrates that the growth trend of energy consumption in China corresponds with the national economic, energy and environmental policies. Primary energy consumption started to surge in 2002, when China joined the WTO and advocated developing an open economic system and expanding manufacturing, with a 15.06% growth rate of primary energy consumption on average from 2002 to 2009. However, in late 2009, with the targets and actions pledged under the Copenhagen Accord, the Chinese government committed to reducing national energy consumption by 40%-45% compared to the consumption in 2005 and allocated this target to the provincial level. This energy-saving trajectory has been effective since the growths of China's primary and final energy consumption have slowed down: from 2010 to 2015, primary and final energy consumption increased by only 3.04% and 2.65% per year, on average, respectively.

However, at the same time, we find that the inter-provincial gap in primary energy intensity (plotted as columns, sum of inequality in final energy intensity, inequality in energy transformation and their interaction) is rising while the growth rate of energy intensity is decreasing. Before 2007, the inequality in energy intensity within China almost remained below 0.6 in all years, with 1996 and 2000 being the only two exceptions, when energy intensity reached 0.6060 and 0.6350 respectively. In contrast, after 2008, inequality in primary energy intensity is generally higher and fluctuates with an average of 0.6635.

The main contributor to this inequality is the inequality in final energy intensity [28], contributing 57.41% on average, although its influence has shrunk from 60.21% in 1995 to 25.53% in 2016. Meanwhile, the contribution of inequality in the energy transformation rate increased to 48.51% in 2016. The energy transformation rate is expressed as the quotient of primary energy consumption and final energy consumption, which is inversely proportional to the energy transformation efficiency. The enlarging gap between provincial primary and final energy consumption probably indicates unequal inter-provincial energy transfer, diverse energy conversion technology during transformation and severe transport loss, etc. [29].

The interaction between final energy intensity and the energy transformation rate is always positive, indicating that provinces with higher final energy intensity tend to have lower energy transformation efficiency. This reveals that energy depletion during transportation may be more severe and energy processing technology may be less advanced in the regions with highest energy intensities, which are the central and western provinces of China.

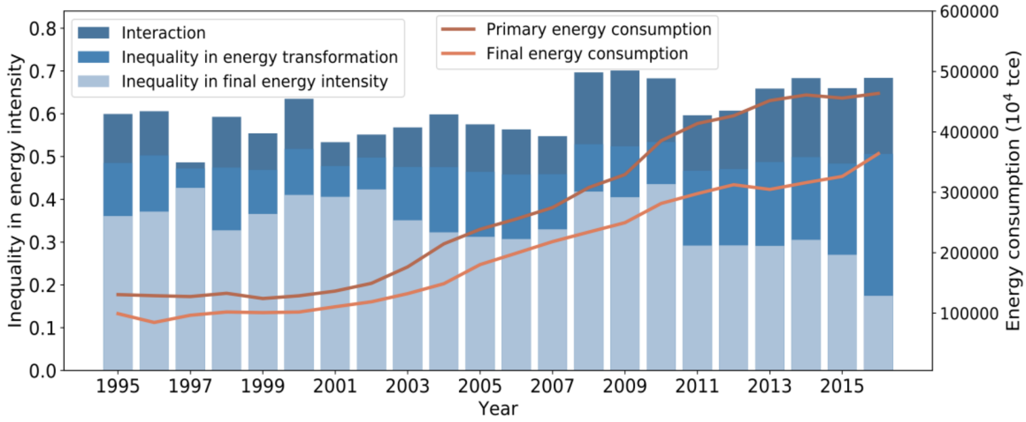


**Fig. 3-1 | Evolution of inequality in energy intensity and energy consumption.** Interaction in the legend denotes the interaction between energy transformation rate and final energy intensity disparities. Inequality in energy intensity is plotted as the columns (sum of inequality in energy transformation rate, inequality in final energy intensity and their interaction).

Fig. 3-2 shows the distribution of primary and final energy intensity in different years (GDP deflated to 1995) and verifies the inequality index in energy intensity in Fig. 3-1 mutually. Fig. 3-2a reveals that while the lowest level of primary energy intensity remains almost the same among the 30 provinces, the highest level of primary energy intensity increases from 902.8 to 3124.7 tonnes standard coal equivalent (tce) per million RMB from 1995 to 2016. The disparity in final energy intensity is also increasing but with a much smaller extent. The difference between the provinces with the highest and the lowest final energy intensity increased from 357.05 tce per million RMB in 1995 to 1006.6 tce per million RMB in 2009 and 1863.4 tce per million RMB in 2016.

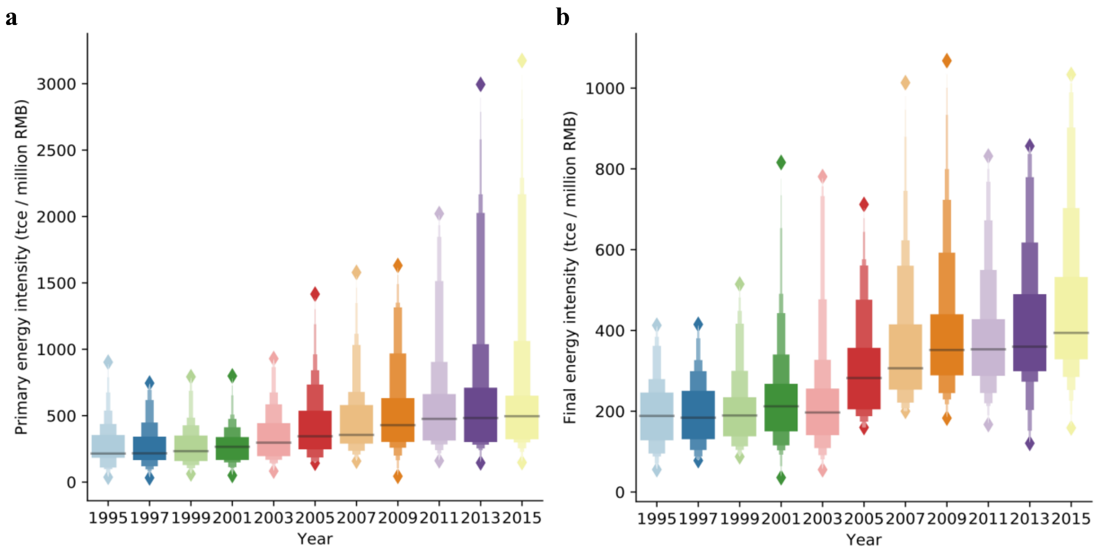


**Fig. 3-2 | Energy intensity distribution. a**, Primary energy intensity distribution. **b**, Final energy intensity distribution.

One of the most obvious advantages of the Zenga index is that it can clearly show which part in the distribution contributes most to the overall inequality [30]. We create inequality charts of energy intensity from 1995 to 2016 to show this property. Since the shape of the inequality charts of energy intensity is similar in adjacent years, only 1 in 3 years is shown in this paper (Fig. 3-3). The x-axis denotes the accumulated share of provincial GDP ordered in ascending primary energy intensity. From Fig. 3-3, we can figure that the left and right end of the inequality curve is rising, indicating provinces with highest and lowest primary energy intensity contribute more to inequality in energy intensity. In other words, energy intensity within China is strongly polarized: provinces with moderate energy intensity level seem to disappear relative to those at the bottom and the top. We will discuss multi-polarization trend of energy intensity within China in more detail in the next section. The contribution of the energy transformation rate, final energy intensity and their interaction to inequality in primary energy intensity is almost unchanged in the early years. However, in recent years, inequality in the energy transformation rate and the interaction between the energy transformation rate and final energy intensity play a greater part in the inequality in primary energy intensity (shown as year=2013 and year=2016 in Fig. 3-3). This shows that these provinces, such as Gansu, Qinghai, Shanxi, Shaanxi, and Guizhou, may have less advanced green technology and bear more heavy industrial transfer from other more developed provinces.

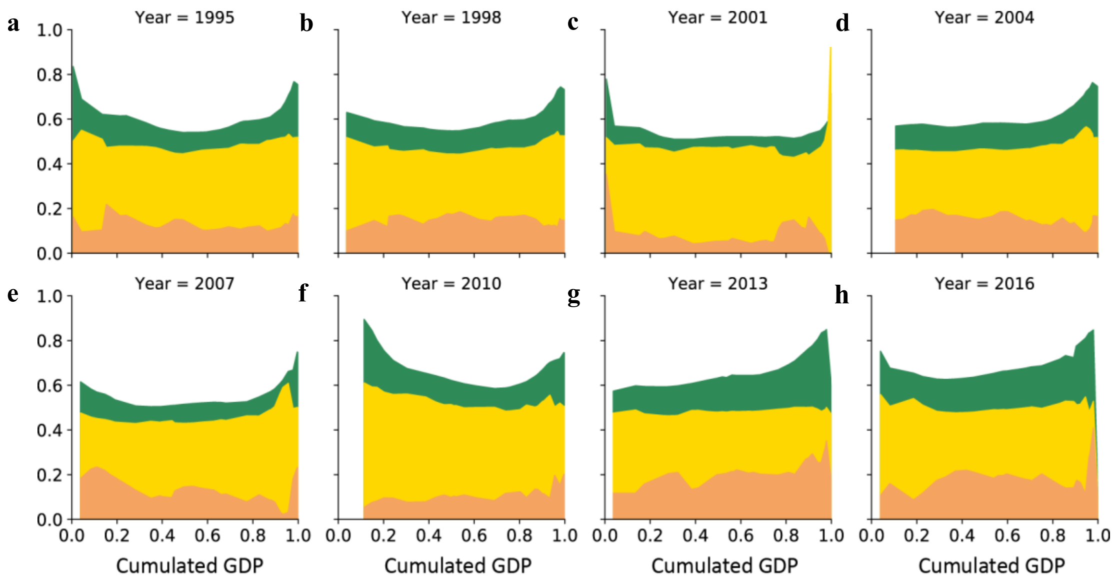


**Fig. 3-3 | Zenga index of Energy Intensity of selected years.** The contribution of energy transformation rate (brown), final energy intensity (yellow) and their interaction (green) to inequality in primary energy intensity in different provinces. The x-axis denotes accumulated the share of provincial GDP ordered in ascending primary energy intensity.

## 3.2. Multi-polarization trend of energy intensity

Polarization is a relative but also distinctive concept from inequality [32-33]. Knowledge of energy intensity polarization is very effective in guiding reductions agreements and mitigating potential instability [34]. According to Zhang & Kanbur (2001) [35], the exogenous energy intensity polarization can be expressed by the Z-K index, which is the quotient of the sum of between-group energy intensity inequality and the sum of within-group energy intensity inequality. Following a lot of existing literature [36-37], we divide China into three economic regions exogenously (the East, the Middle and the West, see Supplementary Fig. 1), to construct the between-group and within-group inequality indexes. The "Five-Year Plan" (FYP) in China is a series of economic, environmental and social development guidelines issued once in five years, which provides the predominant development targets in China. Since China's targets and efforts in mitigating energy consumption vary a lot during different FYP periods, we further divide our whole evaluated period into 6 FYP periods, and measure the average Z-K index during each FYP period.

**Table 3-1 | Z-K index within China during 6 FYP periods**

| FYP | Period | I(E) | Between 1 & 2 | Between 1 & 3 | Between 2 & 3 | Within 1 | Within 2 | Within 3 | Z-K index |
|---|---|---|---|---|---|---|---|---|---|
| 8th FYP | 1995 | 0.5995 | 0.2153 | 0.1438 | 0.05448 | 0.1326 | 0.0318 | 0.0216 | 2.2235 |
| 9th FYP | 1996-2000 | 0.5978 | 0.1980 | 0.1732 | 0.0495 | 0.1284 | 0.0285 | 0.0202 | 2.4728 |
| 10th FYP | 2001-2005 | 0.5654 | 0.1588 | 0.1668 | 0.0502 | 0.1428 | 0.0225 | 0.0242 | 1.9874 |
| 11th FYP | 2006-2010 | 0.6384 | 0.1061 | 0.2164 | 0.1092 | 0.1038 | 0.0199 | 0.0830 | 2.0852 |
| 12th FYP | 2011-2015 | 0.6413 | 0.1946 | 0.1968 | 0.0769 | 0.0988 | 0.0477 | 0.0266 | 2.7107 |
| 13th FYP | 2016 | 0.6828 | 0.0979 | 0.2321 | 0.1491 | 0.0684 | 0.0206 | 0.1147 | 2.3522 |

**Notes:** Between and Within denote between-group effect and within-group effect, respectively; Numbers 1, 2 and 3 denote three exogenous groups (the East, the Middle and the West, see Supplementary Fig. 1), respectively; The whole results for the Z-K index are displayed in Supplementary Table 1.

From the decomposition results, we observe that during every FYP period, the average Z-K index is higher than 1.9, indicating provincial energy intensities within China are strongly polarized. The provincial energy intensity gaps between the East and the Middle (Between 1 & 2), between the East and the West (Between 1 & 3) and within the East (Within 1) are the most significant during most FYP periods, showing that provincial energy intensities in the East are generally lower than those of the Middle and the West, but still quite diversified. Another interesting finding is that the Z-K index was relatively high during the 9th, 11th, 12th and 13th FYP periods, when China attaches importance to energy-saving and low-carbon development. The greatest decrease in the Z-K index occurred during the 10th FYP period, when the central authorities transformed China’s industrial sector into re-heavy-industrialization and set no official energy-saving target [38]. However, more recently, with climate change mitigation institutionalized in economic planning, the inequality index within one economic region is relatively decreasing, reflecting the within-region convergence of energy intensity caused by regional economic integration. Meanwhile, the between-group energy intensity index is relatively increasing, indicating that different economic zones are at different stages of development; hence, the implementation of energy-conservation and emission-reduction targets is diverse across regions.

## 3.3. Driving factors for inequality in energy intensity

What are the possible causes of inequality in energy intensity? According to our calculation results in Fig. 3-1, with provincial final energy intensity converging, inequality in energy intensity is increasingly caused by inequality in energy transformation rate. Energy transformation rate disparities are mainly caused by energy consumption structure, energy conversion rate and inter-provincial energy transfers [29].

Here, we first adopt the Zenga index to identify the contribution of energy consumption structure to inequality in energy intensity. We select five types of primary energy - coal, oil, gas, primary electrical energy and other - and explore their effects on inequality in energy intensity (see Fig. 3-4). The results show that the discrepancy in energy-saving efforts and the regional consumption of different energy sources greatly enlarges the regional gap in energy intensity. As the predominant energy for the western region of China, coal consumption is the main factor driving up inequality in energy intensity. However, due to lack of law and effective management, measures for mitigating coal consumption are currently limited [39]. For instance, coal usage for heating during the winter is a great contribution of loose coal consumption in rural China [40], but is difficult to be tracked because of the geographically disperse consumption pattern of loose coal. On the other hand, energy sources more commonly-used in the eastern region of China (oil, natural gas and electricity) reduce the inequality, partly because their usage is more centralized and easier to be tracked and regulated. In addition, as China’s oil, gas and electric power industries are under administrative monopoly by the central government, these industries may have more incentives to reinforce efforts to reduce environmental and climate-change impacts of their products.

The significantly enlarging disparities in the energy transformation rate are also due to frequent inter-regional energy flows within China, including both secondary energy trade (energy transfer between provinces) and cement product trade (non-energy use). As the Middle and the West become specialized in heavy industries [41], these regions become net exporters of embodied primary energy from inter-regional bilateral trade [42] and may consume more energy producing these products. Evidence of the expanding inter-regional trade in energy consumption can be found in existing literature based on the multi-regional input-output (MRIO) model [43]. The use of MRIO analysis has proved that the inter-regional trade triggered energy consumption and carbon emissions tripled at the national level between 2002 and 2007, with relatively large structural changes among regions.

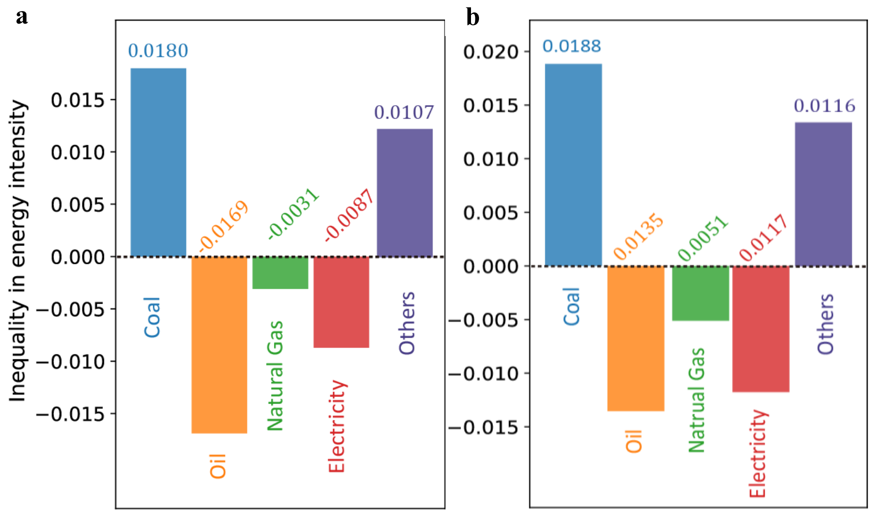


**Fig. 3-4 | Driving factors of inequality in energy intensity. a-b**, Charts showing the contribution of five primary energy sources to inequality in final energy intensity in 2016. **a**, inequality contributed by the consumption structure of the five primary energy sources. **b**, inequality contributed by the interaction between disparities in final energy intensity and the consumption structure of these five primary energy sources.

The enlarging gap in inequality in energy intensity may also be due to a portfolio of energy-saving policies. Under the 12th FYP, China allocated different quotas to provinces in regard to cutting their energy consumption per GDP unit by 2015. The target and actual energy intensity reduction are shown in Fig. 3-5. In this plan, provinces with highest energy intensity, Gansu, Qinghai, Shanxi, Shaanxi, and Guizhou, are only regulated to cut their energy intensity by 16%, 15%, 16%, 15%, and 10%, less stringent targets than those of provinces with lower energy intensity: the 5 provinces with the lowest energy intensity in 2010 all had an energy-saving target of 17% or higher. The only three provinces that failed to achieve their energy-saving goals - Guizhou, Ningxia, and Xinjiang -, were all provinces with high energy intensity located in western China. The regional allocation of energy intensity goals is now based on the “common but differentiated” burden sharing rules [7]. While the Middle and the West may have the obligation to save more energy due to their higher accumulated energy consumption in the past, they still need to focus on achieving economic development [8-9]. Due to energy technological progress and structural shifts towards the manufacturing of processed products [45], the energy intensity in the East is controlled under the 12th FYP, while the Middle and the West may have undertaken energy-intensive industrial transfer from the East and focused more on economic development. Since the raw-material-intensive industrial transfer within China is untraceable because the enterprises may change their names and legal codes, we can only find news articles on industrial transfer: many high-emission enterprises have been reported to relocate from oriented regions to regions with lower energy-saving standards, or be shut down, due to stricter energy-saving requirements.

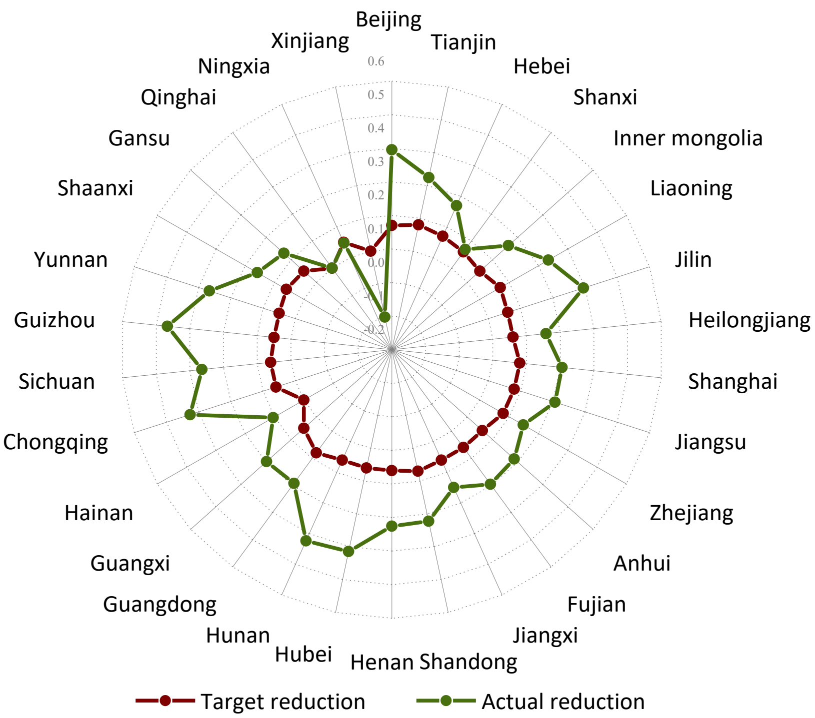


**Fig. 3-5 | Energy intensity reduction (%) during the 12th FYP**. Provincial actual reduction (red, %) and target reduction (green, %) during the 12th FYP.

# 4. Discussions and Policy Implications

## 4.1 Discussions

In recent years, China's energy consumption has grown continuously, causing the contradiction between natural resources, the environment and economic growth to become increasingly prominent. Many measures are taken to reduce China's energy intensity, which have achieved remarkable results, but at the same time, amplified inequality in energy intensity. United national energy intensity is largely hindered by provinces with the highest energy intensities. From 2011 to 2016, on average 30.59%, 31.73% and 37.68% inequality in energy intensity are contributed by the least 10, middle 10 and top 10 energy-intense provinces. What's more, the energy intensity gap is enlarging between different economic clubs. The inequality in energy intensity between the East, the Middle and the West is almost three times as large as inequality in energy intensity within these economic clubs, indicating that the energy intensity distribution in China is getting polarized.

The inequality in energy intensity is more and more contributed by the inequality in energy transformation rate (i.e., the quotient of primary energy consumption and final energy consumption). This reflects three facts: (i) rather loose regulatory measures on mitigating coal consumption; (ii) increasing inter-regional energy fluxes embodied in trade; (iii) separate jurisdictions at provincial administrative levels. From the perspective of the energy consumption structure, the main driver of energy intensity inequality is coal consumption, while natural gas, oil and electricity consumption is currently inhibiting this trend. This may result in more severe inequality in energy intensity in the future, since energy-saving efforts are reinforced better by mitigating the consumption of petroleum, gas and electricity. Besides, inequality in energy intensity is a result of increasing net embodied energy fluxes moved from the middle and western regions of China to the coastal regions through closer inter-regional trade in domestic supply chains, which has been constantly proved by many empirical studies. Another plausible explanation for increasing inequality in energy intensity is the regionally unbalanced allocation of energy-saving goals in the FYP. The middle and western regions of China are less motivated to cut their energy intensities as these regions bear a lighter burden to reduce their energy intensities.

The three factors mentioned above can synthetically intrigue some energy-intensive and coal-intensive enterprises to relocate to the Middle and the West, regions with severe energy problems and inferior green technologies. In the short term, the inequality and polarization in energy intensity within China is very likely to continue to increase. According to the 13th FYP (2015-2019), energy consumption control for different provinces will still be categorized. The intention of categorized energy intensity constraint is to promote economic growth and optimize resource allocation efficiency [46]. However, as our study shows, this may also result in a rigescent energy consumption structure and heavy industry agglomeration in regions with less-advanced green technology, thus leading to inequality and polarization in energy intensity and resulting in an overall obstructive effect on energy-saving.

## 4.2 Policy implications

Therefore, more attention should be paid to the balanced development of energy consumption across different regions and energy sources towards low-carbon energy transitions and energy intensity convergence [47-48]. Regional development strategies should comprehend energy conservation and emission reduction and mix more efforts in green policy. The Middle and the West should adapt to local conditions and promote upgrading of the industrial structure, optimization of the energy structure, and synergy of inter-regional technological innovation. The eastern region of China should promote energy processing technology spillovers, eliminate high-energy-consuming enterprises instead of transferring them, and develop clean and renewable energy sources [49]. Unlike conventional energy, renewable energy is more available of local resources [50] and can be applied in final services directly without fuel or power generation, transport and import. Ongoing work involves deeper research on the requirements for success in these pathways.

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# Appendix


**Supplementary Figure 1 | Geographical distribution of eastern, central and western China.** The literature usually categorizes mainland China into three regions (eastern, central and western China) on the basis of geographical proximity and development stage. Due of data availability, Tibet in western China is not covered in this study.

**Supplementary Table 1 | Conversion factors from physical units to coal equivalent ($10^4$ tce )**

| Fossil fuel types | Conversion factor | Fossil fuel types | Conversion factor |
|---|---|---|---|
| Raw Coal ($10^4$ tonnes) | 0.7143 | Fuel Oil ($10^4$ tonnes) | 1.4286 |
| Cleaned Coal ($10^4$ tonnes) | 0.9000 | Naphtha ($10^4$ tonnes) | 1.5000 |
| Other Washed Coal ($10^4$ tonnes) | 0.4643 | Lubricants ($10^4$ tonnes) | 1.4143 |
| Briquettes ($10^4$ tonnes) | 0.6000 | Paraffin Waxes ($10^4$ tonnes) | 1.3648 |
| Gangue ($10^4$ tonnes) | 0.2857 | White Spirit ($10^4$ tonnes) | 1.4672 |
| Coke ($10^4$ tonnes) | 0.9714 | Bitumen Asphalt ($10^4$ tonnes) | 1.3307 |
| Coke Oven Gas ($10^8$ cu.m) | 5.7140 | Petroleum Coke ($10^4$ tonnes) | 1.0918 |
| Blast Furnace Gas ($10^8$ cu.m) | 1.2860 | LPG ($10^4$ tonnes) | 1.7143 |
| Converter Gas ($10^8$ cu.m) | 2.7140 | Refinery Gas ($10^4$ tonnes) | 1.5714 |
| Other Gas ($10^8$ cu.m) | 1.7860 | Other Petroleum Products ($10^4$ tonnes) | 1.4000 |
| Other Coking Products ($10^4$ tonnes) | 1.1000 | Natural Gas ($10^8$ cu.m) | 13.3000 |
| Crude Oil ($10^4$ tonnes) | 1.4286 | LNG ($10^4$ tonnes) | 1.7572 |
| Gasoline ($10^4$ tonnes) | 1.4714 | Heat ($10^{10}$ kJ) | 0.0341 |
| Kerosene ($10^4$ tonnes) | 1.4714 | Electricity ($10^8$ kW h) | 1.2290 |
| Diesel Oil ($10^4$ tonnes) | 1.4571 | Other Energy ($10^4$ tce) | 1.0000 |