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Energy efficiency, carbon dioxide emission efficiency, and related abatement costs in regional China: a synthesis of input–output analysis and DEA

Yu Cheng · Kangjuan Lv · Jian Wang ⬤ · Hao Xu

Abstract This paper attempts to examine energy efficiency, carbon dioxide (CO_2) emission efficiency, and related abatement costs of China's regions in 2012 by considering embodied carbon caused by trade. To this end, a combined approach with environmentally extended input–output analysis (EEIO) and DEA is proposed. We first apply the EEIO model to measure CO_2 emissions of 30 China's regions from the consumption perspective, which can identify the described embodied carbon. According to the amounts of CO_2 emissions with respect to the production-based and consumption-based principles, 30 regions are divided into two groups, i.e., emission-importing regions and emission-exporting regions. For emission-importing regions, CO_2 emissions from the consumption perspective exceed that from the production-based perspective. The emission-exporting regions exhibit the opposite case. Our results show that energy efficiency and CO_2 emission abatement costs will be underestimated in both groups when ignoring the embodied carbon emissions. The emission-importing regions evidence higher efficiency scores and abatement costs than those emission-exporting regions, and there is a significant difference between these two groups in terms of energy efficiency and CO_2 emission efficiency, whereas there is no significant difference with respect to CO_2 emission abatement costs. It is interesting that emission-exporting regions enjoy a slight increase in CO_2 emission efficiency whereas emission-importing regions suffer from a decrease. Some useful policy implications are achieved.

Keywords Environmentally extended input–output analysis · Data envelopment analysis · Energy efficiency · CO_2 emission efficiency · CO_2 emission abatement costs

Y. Cheng · K. Lv · J. Wang (✉)
SHU-UTS SILC Business School, Shanghai University, Shanghai 201899, People's Republic of China
e-mail: jianwang@shu.edu.cn

Y. Cheng
e-mail: ahngchy@126.com

K. Lv
e-mail: lvkangjuan@shu.edu.cn

H. Xu
School of Business, Anhui University, Hefei 230601 Anhui Province, People's Republic of China
e-mail: xuhaoau@126.com

Introduction

China's remarkable economic achievements over the past decades have led to great energy consumptions and related CO_2 emissions. More recently, China has overtaken the USA, and been the largest energy consumer and CO_2 emitter in the world (Lin and Zhu. 2017). The primary energy consumption of China in 2014 reached 2971 million tonnes (Mt), which accounts for roughly 23% of global total energy consumption and is larger than that of the USA (Jiang et al. 2017). According to World Bank (2014), China emitted 10,291.93 Mt CO_2 emissions in 2014, while the

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corresponding figure of the USA was 52,542.79 Mt. In response to such circumstance, China has launched great efforts to improve energy efficiency and reduce carbon intensity. For example, the central government announced to lower its energy intensity (energy consumption per unit of GDP) by 20 and 16% during the eleventh 5-year plan period (2006–2010) and the twelfth 5-year plan period (2011–2015), respectively. As we know, China has committed to reduce CO_2 intensity (CO_2 emissions per unit of GDP) by 40–45% by 2030 compared with the 2005 level (Yan 2015). These targets seem to be inspiring, but how to realize them? Due to the fossil energies (i.e., coal, crude oil, and natural gas) dominated energy consumption structure in China, it is hard to substantially reduce energy consumptions. Thus, it is appropriate to improve energy efficiency and CO_2 emission efficiency in order to reduce energy consumption and related CO_2 emissions.

Notably, those energy intensity and CO_2 intensity reduction targets are formulated at the national level. However, such targets still need to be implemented by all regions in the country. Owning to the prominent differences in resource endowment, economic development, and technological progress across regions in China, energy efficiency and CO_2 emission efficiency are significantly different across regions, and thus, it is unreasonable and unfair to set common energy saving and carbon reduction targets and standards for all regions (Liu et al. 2015). Common wisdom suggests that achieving any emission reduction target is costly, which means that economic output would be affected by the reduction of CO_2 emissions. Thus, there is a commonly trade-off between economic growth and carbon reduction. Generally speaking, in any economic production activity, energy resources and other non-energy materials (e.g., labor and capital) are utilized to produce desirable outputs (e.g., GDP) and undesirable outputs (e.g., CO_2 emissions) simultaneously, and the undesirable outputs can be seen as the by-products of desirable outputs (Wang et al. 2017). Thus, the marginal abatement costs of CO_2 emissions can be expressed as the opportunity costs of reducing one additional unit of CO_2 emissions in terms of the corresponding decrease of GDP. With these considerations, it is necessary to estimate CO_2 emission abatement costs in China.

In the existing studies, the amount of CO_2 emission is usually estimated from the production perspective according to the production-based principle. Such principle also known as the territorial principle declares that one region should be responsible for the CO_2 emissions that directly caused by local production activities (Zhang 2015). Under this principle, most extant studies estimate CO_2 emissions based on the consumptions of energies, i.e., Li et al. (2012), Liu et al. (2016), and Lv et al. (2017). As well known, carbon emissions are emitted when end products being consumed rather than manufactured. In this regard, we argue that it may not be suitable to estimate CO2 emissions with the production-based principle. To be specific, alongside the international trade liberalization and regional integration, especially the trade of intermediate products, the production-based accounting has been criticized for its ignorance of carbon leakage issues (Zhang 2013; Fan et al. 2016). The reason for this is that one region can achieve its emission reduction commitment and improve carbon emission efficiency by importing carbon-intensive products from other regions or countries to satisfy its local demand. In such case, the carbon embodied in these products will be emitted in the region. Thus, given the consideration of fairness, it is difficult to determine the responsibility of carbon reductions that one region should undertake (Liu et al. 2015). Consequently, it is necessary and more suitable to estimate CO_2 emissions from the consumption perspective.

The above evidence raises the following important issues: (1) How to measure energy efficiency, CO_2 emission efficiency, and related abatement costs? (2) How to estimate CO_2 emissions underlying the consumption perspective?

In the literature, data envelopment analysis (DEA) has been widely applied to examine energy efficiency and carbon emission efficiency. Hu and Wang (2006) first develop the concept of total-factor energy efficiency based on DEA approach. However, the variable of CO_2 emissions is ignored in their study. By taking CO_2 emissions into consideration, Wang et al. (2012) and Wang and Wei (2014) further address such issues. Note that these two streams of studies use radial measure to evaluate the efficiency, which requires all inputs or outputs are proportionally contracted or expanded. Thus, it is limited to recognize efficiency performance for a specific input or output (Fukuyama and Weber 2009). To overcome such weakness, some studies propose non-radial measures to estimate the efficiency. The most widely used one is the slack-based measure (SBM) introduced by Tone (2001). This measure can deal with input excess and output shortfall to avoid the inaccuracy of efficiency caused by slacks. This property is

especially suitable for exploring energy saving and un-desirable output reductions (e.g., CO_2 emissions) (Zhang and Choi 2013). Based on such non-radial meth-od, Li and Hu (2012) measure the total-factor energy efficiency of 30 Chinese provinces from 2005 to 2009 by treating CO_2 and SO_2 as undesirable outputs. Li and Shi (2014) investigate energy efficiency and related influential factors at Chinese industrial level from 2001 to 2010 based on an improved super-SBM model. Bi et al. (2014) explore the energy efficiency and envi-ronmental efficiency of thermal power generation in China during 2007–2009. Liu et al. (2016) examine Chinese regional CO_2 emission efficiency from 2000 to 2011. It is noteworthy that these studies have not considered the weak disposability of undesirable out-puts. As we know, any production activity is a joint-production process, in which desirable and undesirable outputs are produced together. Any reduction in undesirable outputs will lead to a decrease in desirable outputs. In such a circumstance, the linkage between GDP and CO_2 emissions should be considered when measuring energy efficiency or CO_2 emission efficiency. Such consideration can be found in the most recent studies, e.g., Wang et al. (2017) and Lv et al. (2017).

Since CO_2 emissions are non-marketable and cannot be priced appropriately in practice, shadow price is usually used to estimate the marginal abatement costs of CO_2 emissions (Choi et al. 2012). Some studies directly examine the abatement costs of CO_2 emission at regional or industrial level based on the traditional DEA method. For example, Wang and Wei (2014) esti-mate the industrial CO_2 emission abatement costs for 30 China's major cities through an improved distance func-tion approach. Zhou et al. (2015) apply multiple dis-tance function approaches to evaluate the shadow prices of CO_2 emissions of industrial sectors in Shanghai dur-ing 2009–2012. Note that these studies adopt radial efficiency measures to conduct their analysis (Wang et al. 2017). Base on the SBM model, Choi et al. (2012) and Wei et al. (2012) estimate regional abate-ment costs of CO_2 emissions with the dataset from 2001 to 2010 and from 1995 to 2007 in China, respectively. Nevertheless, the weak disposability assumption of CO_2 emissions is not imposed in their models. The only exception is Wang et al. (2017). They examine CO_2 emission abatement costs of city areas in China by considering the linkage between GDP and CO_2 emissions.

To address the second described issue, the consumption-based accounting principle has been intro-duced to measure CO_2 emissions based on the final product consumptions within a region. Most related studies have adopted input–output (IO) analysis, known as a quantitative methodology for modeling systems covering complex interdependencies of industries, to calculate CO_2 emissions. This approach is firstly pro-posed by Leontief (1936), and has been widely employed to examine economic, social, and environ-mental issues (Su and Ang 2013; Lee and Yoo 2016). Such approach has been extended to an improved one that further considers variables regarding natural re-sources and environmental pollutants, i.e., environmen-tally extended input–output (EEIO) analysis. EEIO combines economic activities with sector resource use and emissions, and attributes environmental pressures according to final consumption (Zurano-Cervelló et al. 2017). Based on EEIO analysis, Zhang (2013) and Mi et al. (2017) evaluate responsibility of CO_2 emissions at the sectoral and regional level in China, respectively. Some recent studies conduct comparisons between pro-ducer responsibility and consumer responsibility asso-ciated with CO_2 emissions (Peters 2008; Fan et al. 2016). In particular, Liu et al. (2015) and Mi et al. (2017) demonstrate that there exist great differences between the two accounting principles (i.e, production-based and consumption-based principles) on regional emissions in China.

Notably, the above-mentioned studies mainly focus on examining regional emission responsibilities under the two accounting principles rather than the efficiency issues. Recently, Egilmez et al. (2013) and Zurano-Cervelló et al. (2017) evaluate the eco-efficiency of manufacturing sectors in the USA and European Union by combining IO analysis and DEA approach, respectively. In their studies, environmental impacts are regarded as inputs and the single output is economic output. These indicators are not reasonable in real efficiency evaluation, for that undesirable environmental factors are outputs rather than inputs, and other inputs such as labor, energy capital are ignored. Tian and Lin (2017) use the directional distance function approach to estimate the green productivity growth in China's industrial exports, but they have not addressed the issues of energy efficiency, CO_2 emission efficiency and the abatement costs of CO_2 emissions.

In order to estimate energy efficiency, CO_2 emission efficiency and abatement costs of regions in China, we

in this study propose a combined approach with both input–output analysis and SBM model. First, we use environmentally extended input–output model to estimate CO_2 emissions from the consumption perspective by using the dataset of the input–output tables in 2012. We then further examine energy efficiency, CO_2 emission efficiency and abatement costs of China's regions in 2012 by using the introduced SBM model. The main contributions of our work to the literature are summarized as follows. First, CO_2 emissions are estimated from the consumption perspective at regional level in China rather than the production perspective like most related studies. This can contribute to better identify ultimate source of carbon emissions. Second, energy efficiency and CO_2 emission efficiency are measured under SBM framework by considering the weak disposability of CO_2 emissions, which is different from the related work, e.g., Choi et al. (2012). To the best of our knowledge, this is the first study to examine the issues of efficiency and abatement costs by combining both input–output analysis and SBM model with the consideration of the weak disposability of CO_2 emissions. Third, to better identify the sources of inefficiency, we classified 30 regions into two groups (i.e., emission-importing regions and emission-exporting regions) rather than three widely used groups, i.e., the eastern area, central area, and western area in the previous studies.

The rest of this paper is organized as follows. Section "Methodology" firstly introduces environmental extended input–output analysis, and then the evaluation approach regarding energy efficiency, CO_2 emission efficiency, and marginal abatement costs. The variables, data sources, and results are presented in Section "Empirical analysis." Section "Conclusions and policy implications" offers conclusions and policy implications.

Methodology

In this section, we first present the environmental extended input–output model, and the efficiency evaluation method and the abatement cost estimation approach based on the SBM model.

Environmentally extended input–output model

Following Su and Ang (2013) and Su et al. (2017), the standard framework of IO analysis can be expressed as:

$$x = Z_d \bullet 1 + y_d + y_e = A_d x + y_d + y_e \qquad (1)$$

In model (1), x is the vector of total output; Z_d is the matrix of domestic intermediate demand; $A_d = Z_d \bullet (\hat{x})^{-1}$ is the matrix of domestic production coefficient; y_d represents the vector of domestic final consumption, which contains private consumption, government consumption, and capital formation; and y_e is the vector of domestic export of each sector. Model (1) can be rewritten as

$$x = (I - A_d)^{-1}(y_d + y_e) \qquad (2)$$

Note that $L_d = (I - A_d)^{-1}$ is the Leontief inverse matrix. Consider that f is the vector of emission coefficients representing the CO_2 emissions per unit of output, and then total amount of CO_2 emissions from production can be obtained by using the following model:

$$C_{tot} = f \bullet x = f(I - A_d)^{-1}(y_d + y_e) = fL_d y_d + fL_d y_e$$
$$= C_d + C_e \qquad (3)$$

In this model, C_{tot} is the total CO_2 emissions from production; C_d and C_e are defined as the emissions embodied in domestic final demand and emissions embodied in export, respectively. This environmentally extended input–output model has been widely used to calculate CO_2 emissions in the literature (Zhang 2013; Ou et al. 2017). Notably, the above framework is built upon the single-regional input–output model instead of the multi-regional input–output model. The main difference between these two models is that the single-regional input–output model cannot capture the amount of embodied carbon transferring through interprovincial and international trade exactly. Since the attempt of this work is to estimate the demand-driven CO_2 emissions within a certain region, and further address the associated efficiency issue rather than carbon transferring caused by merchandise trade, we then, for simplicity, use single-regional input–output model accordingly.

Efficiency and abatement cost estimation approach

Suppose that there are n decision-making units (DMUs, $j = 1, 2, \ldots, n$), representing regions of China. In production, DMU_j employs labor (XL_j), capital stock (XK_j), and energy (XE_j) as inputs to produce GDP (YG_j) as desirable output and generate CO_2 emissions (YC_j) as undesirable output. As discussed in the previous section,

any economic production activity could be seen as a joint-production process in which multi-inputs are utilized to produce desirable outputs and undesirable outputs. Notably, undesirable outputs such as CO_2 emissions cannot be reduced freely and it is weakly disposable (Färe and Grosskopf 2004). Consequently, the relationship between GDP and CO_2 emissions should be considered when measuring the energy efficiency or CO_2 emission efficiency. Following Chang et al. (2014) and Wang et al. (2017), a modified SBM model that considering the linkage between GDP and CO_2 emissions is derived, i.e.,

$$\theta_0 = \min \frac{1 - \frac{1}{3}\left(\frac{s_0^l}{XL_0} + \frac{s_0^k}{XK_0} + \frac{s_0^e}{XE_0}\right)}{1 + \frac{1}{2}\left(\frac{s_0^g}{YG_0} + \frac{s_0^c}{YC_0}\right)}$$

s.t.

$$\sum_{j=1}^{n} \lambda_j XL_j + s_0^{l-} = XL_0,$$
$$\sum_{j=1}^{n} \lambda_j XK_j + s_0^{k-} = XK_0,$$
$$\sum_{j=1}^{n} \lambda_j XE_j + s_0^{e-} = XE_0, \qquad (4)$$
$$\sum_{j=1}^{n} \lambda_j YG_j - s_0^{g+} = YG_0,$$
$$\sum_{j=1}^{n} \lambda_j YC_j + s_0^{c-} = \left(1 + \frac{s_0^{g+}}{YG_0}\right) YC_0,$$
$$\lambda_j, s_0^{l-}, s_0^{k-}, s_0^{e-}, s_0^{g+}, s_0^{c-} \geq 0, j = 1, 2, \ldots, n.$$

In model (4), the subscript "0" represents the regions to be evaluated, and θ_0 is the corresponding efficiency value. s_0^{l-}, s_0^{k-}, s_0^{e-}, s_0^{g+}, and s_0^{c-} denote the slack variables regarding labor, capital, energy, GDP, and CO_2 emissions, respectively. λ_j is the intensity variable for connecting inputs and outputs. Note that, model (4) is similar to the traditional SBM model developed by Tone (2001) except the constraint $\sum_{j=1}^{n} \lambda_j YC_j + s_0^{c-} = \left(1 + \frac{s_0^{g+}}{YG_0}\right) YC_0$. Such constraint meets the requirement of weak disposability of undesirable output. That is, although model (4) can maximize the slack of CO_2 emissions, the number of CO_2 emissions in each region can increase in proportional with the improvement of GDP (Chang et al. 2014). Note that model (4) is a non-linear programming model, and can be transformed into the following linear programming:

$$\theta_0 = \min t - \frac{1}{3}\left(\frac{\varepsilon_0^{l-}}{XL_0} + \frac{\varepsilon_0^{k-}}{XK_0} + \frac{\varepsilon_0^{e-}}{XE_0}\right)$$

s.t.

$$t + \frac{1}{2}\left(\frac{\varepsilon_0^{g+}}{YG_0} + \frac{\varepsilon_0^{c-}}{YC_0}\right) = 1,$$
$$\sum_{j=1}^{n} \eta_j XL_j + \varepsilon_0^{l-} = tXL_0,$$
$$\sum_{j=1}^{n} \eta_j XK_j + \varepsilon_0^{k-} = tXK_0,$$
$$\sum_{j=1}^{n} \eta_j XE_j + \varepsilon_0^{e-} = tXE_0, \qquad (5)$$
$$\sum_{j=1}^{n} \eta_j YG_j - \varepsilon_0^{g+} = tYG_0,$$
$$\sum_{j=1}^{n} \eta_j YC_j + \varepsilon_0^{c-} = \left(t + \frac{\varepsilon_0^{g+}}{YG_0}\right) YC_0,$$
$$\eta_j, \varepsilon_0^{l-}, \varepsilon_0^{k-}, \varepsilon_0^{e-}, \varepsilon_0^{g+}, \varepsilon_0^{c-} \geq 0, j = 1, 2, \ldots, n.$$

Note that $\eta_j = t\lambda_j$, $\varepsilon_0^{l-} = ts_0^{l-}$, $\varepsilon_0^{k-} = ts_0^{k-}$, $\varepsilon_0^{e-} = ts_0^{e-}$, $\varepsilon_0^{g+} = ts_0^{g+}$, and $\varepsilon_0^{c-} = ts_0^{c-}$. By solving model (5), regional overall efficiency θ_0, optimal value of t, and all slack variables can be obtained. When $\theta_0 = 0$, all the slacks are equal to zero, and the evaluated region is said to be efficient; otherwise, it is inefficient.

As for an inefficient region, the efficiency score can be enhanced through slack and radial adjustment (Shi et al. 2010). Thus, based on the target setting approach, we have the following equations to determine the potential energy savings and CO_2 emission reductions:

$$PE_0 = s_0^{e-*} = \frac{\varepsilon_0^{e-*}}{t^*},$$
$$PC_0 = s_0^{c-*} - \frac{s_0^{g-*}}{YG_0} YC_0 = \frac{\varepsilon_0^{c-*}}{t^*} - \frac{\varepsilon_0^{c-*}}{t^* YG_0} YC_0. \qquad (6)$$

Note that PE_0 and PC_0 represent targets for energy savings and CO_2 emission reductions, respectively. Following the idea "ratio of target value to real value" introduced by Hu and Wang (2006), we can obtain energy efficiency scores of all regions in China. This approach has been further extended to calculate CO_2 emission efficiency, e.g., Choi et al. (2012). To be specific, CO_2 emission efficiency can be calculated by the ratio of target CO_2 emissions to real CO_2 emissions (Iftikhar et al. 2016). Hence, energy efficiency (EE_0) and CO_2 emission efficiency (CE_0) for DMU_0 can be measured by:

$$EE_0 = \frac{XE_0 - PE_0}{XE_0},$$
$$CE_0 = \frac{YC_0 - PC_0}{YC_0}. \tag{7}$$

Since the real abatement costs of CO_2 emissions cannot be obtained directly in practice, we introduce the dual model of model (5) to derive the shadow price of CO_2 emissions. Thus, the dual of model (5) is expressed as

$$\rho_0 = \max \rho$$
$$s.t.$$
$$\rho + p^l XL_0 + p^k XK_0 + p^e XE_0 - p^g YG_0 + p^c YC_0 = 1,$$
$$p^l \geq \frac{1}{3XL_0},$$
$$p^k \geq \frac{1}{3XK_0},$$
$$p^e \geq \frac{1}{3XE_0},$$
$$p^g \geq \frac{1}{2YG_0}\rho + p^c\frac{YC_0}{YG_0},$$
$$p^c \geq \frac{1}{2YC_0}\rho,$$
$$p^g YG_j - p^l XL_j - p^k XK_j - p^e XE_j - p^c YC_j \leq 0. \tag{8}$$

Note that p^l, p^k, p^e, p^g, and p^c refer to the dual variables correspond to the constraints of labor, capital, energy, GDP, and CO_2 emissions in model (5), respectively, and ρ is a dual variable correspond to the objective function of model (5). Note that p^c denotes the shadow prices of CO_2 emissions, whereas p^g can be interpreted as the shadow price of GDP. The relative shadow price of CO_2 emissions (SPC) with regard to GDP can be measured by:

$$SPC = 1CNY \times \frac{p^c}{p^g} \tag{9}$$

Therefore, the reasonable price of CO_2 emissions can be obtained from Eqs. (8) and (9). The relative shadow price can be interpreted as the marginal rate of transformation between CO_2 emissions and GDP. This indicates that it is not free but costly for each region to abate CO_2 emissions in production. That is, reducing CO_2 emissions actually leads to economic loss as they incur an opportunity cost associated with reducing desirable output (Choi et al. 2012). Similar abatement cost estimation approach can be found in Wang et al. (2015) and Wang et al. (2017).

Empirical analysis

Regions, variables, and data sources

Mainland China consists of 31 regions (provinces, autonomous regions, and municipalities), which can be divided into three areas: the eastern, central, and western areas (Lv et al. 2017; Wang et al. 2017). The eastern area includes three municipalities of Beijing, Tianjin, and Shanghai and eight provinces, i.e., Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central area is composed of 10 regions, i.e., Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, and Guangxi. The remaining one municipality of Chongqing and nine provinces of Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Tibet belong to the western area. It is noteworthy that Tibet is excluded in this study due to the unavailable data regarding energy consumption and trade.

We in this study take energy consumption, labor, and capital stock as three inputs, GDP and CO_2 emissions as desirable output and undesirable output, respectively. Three types of fossil fuels, namely coal, oil, and natural gas, are converted into standard coal equivalent (SCE) in this study. The data of energy is obtained from China Energy Statistical Yearbook in 2013. The data on labor and GDP is collected from the Statistical Year Book of China in 2013. The data on capital stock is estimated based on the method of Shan (2008), which is also used in the study of Wang et al. (2012) and Lv et al. (2017). With respect to CO_2 emissions, we adopt the 30 provincial input–output tables (ITOs) in 2012 as the dataset to calculate the corresponding data. Notably, since the sector classification in the energy consumption dataset is not consistent with that of the ITOs, we aggregate the existing 42 sectors into 31 sectors to keep the two datasets consistent, which is provided in Table 5 in Appendix. Following Li et al. (2012) and Lv et al. (2017), sectoral CO_2 emissions can be estimated through multiplying the consumption of individual fossil fuels (i.e., coal, crude oil, and natural gas) with their carbon emission coefficients and corresponding conversion coefficients. One can refer to Dai et al. (2009) for more details about the carbon emission coefficients for fossil energies. For most regions, the sectoral energy consumption data can be obtained from provincial Statistical Yearbook in 2013. As for those regions whose sectoral energy consumption data is unavailable, i.e.,

Shanghai, Jiangsu, Zhejiang, and Sichuan, we assign total emissions to sectors based on their energy consumption structures available from China's Economic Census Yearbook in 2008. We also obtain the data on CO_2 emissions from the production perspective. The descriptive statistics of all input and output variables are presented in Table 1.

Regional CO_2 emissions

In this sub-section, we present the data on regional CO_2 emissions accounted under the production-based principle and consumption-based principle in China, respectively. The results are showed in Fig. 1. According to the production-based accounting principle, total national CO_2 emissions are 10,016.25 Mt in 2012, which is higher than that (i.e., 9598.85 Mt) estimated from the consumption perspective. This indicates that the consumption-based approach may attribute less responsibility of CO_2 emissions to China at national level. This result partly supports the pollution haven hypothesis in China due to the extra total CO_2 emissions result from the international trade.

Figure 1 shows that there exist significant differences among regions no matter what accounting measurement adopts. In particular, under the production-based accounting, seven provinces including Shandong, Inner Mongolia, Hebei, Jiangsu, Shanxi, Liaoning, and Henan have emitted CO_2 emissions larger than 500 Mt. Among these regions, Shandong and Jiangsu are supposed to take more responsibility of CO_2 emissions, which are correspondence with their larger economic sizes. Notably, industrial structures of the remaining five regions are dominated by heavy industry. This may be the major reason that leads to higher carbon intensity and total emissions in these regions. By contrast, the economic sizes of Qinghai, Hainan, Beijing, Chongqing, Jiangxi, Tianjin, Ningxia, and Gansu are relatively small, which

can partly explain why their CO_2 emissions are relative low. From the consumption perspective, Shandong, Jiangsu, Guangdong, Inner Mongolia, Hebei, Zhejiang, Liaoning, and Henan are the eight regions with relatively high levels of CO_2 emissions. Notably, Shandong is the biggest regional CO_2 emission emitter in China, regardless of whether the production-based principle or consumption-based principle is applied, i.e., 972.49 Mt and 834.75 Mt, respectively.

According to the data on CO_2 emissions, 30 regions can be classified into two groups, i.e., emission-importing regions and emission-exporting regions. The first group includes those regions whose amount of CO_2 emissions under the consumption-based principle exceeds that under the production-based principle. In this case, these regions are net importers of emissions as they take more responsibility of emissions caused by its local consumptions that do not included in their production activities. The second group is an opposite case. The first group contains 14 regions, including Beijing, Tianjin, Jilin, Shanghai, Jiangsu, Zhejiang, Jiangxi, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, and Yunnan. For example, Beijing's amount of CO_2 emissions is 173.07 Mt under the consumption-based principle, which is 81.43% higher than that caused by local production activities (i.e., 95.39 Mt). This indicates that Beijing is a net emission importer in 2012. Interestingly, most of them are located at the eastern China or the areas that exhibit energy resource shortage. The second group includes the remaining 16 regions, i.e., Hebei, Shanxi, Inner Mongolia, Liaoning, Heilongjiang, Anhui, Fujian, Shandong, Henan, Hubei, Guizhou, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. Each region in this group is regarded as a net emission exporter because its CO_2 emission amount under the consumption-based principle is smaller than that under the production-based principle. Notably, most of these

Table 1 The descriptive statistics of inputs and outputs in 2012

Variable	Unit	Mean	Std. dev.	Min	Max
Labor	10^4 persons	2664.02	1746.54	310.89	6554.30
Capital stock	10^8 CNY	9775.19	7956.90	755.23	29,849.44
Energy	10^4 ton SCE	13,330.41	8590.70	2069.12	38,592.06
GDP	10^8 CNY	19,195.03	13,935.59	1893.54	57,067.92
Production-based CO_2 emissions	10^4 ton	33,387.51	21,672.48	4869.30	97,248.78
Consumption-based CO_2 emissions	10^4 ton	31,996.19	18,885.09	3374.77	83,474.80

Fig. 1 Regional carbon emissions (Mt) in China in 2012
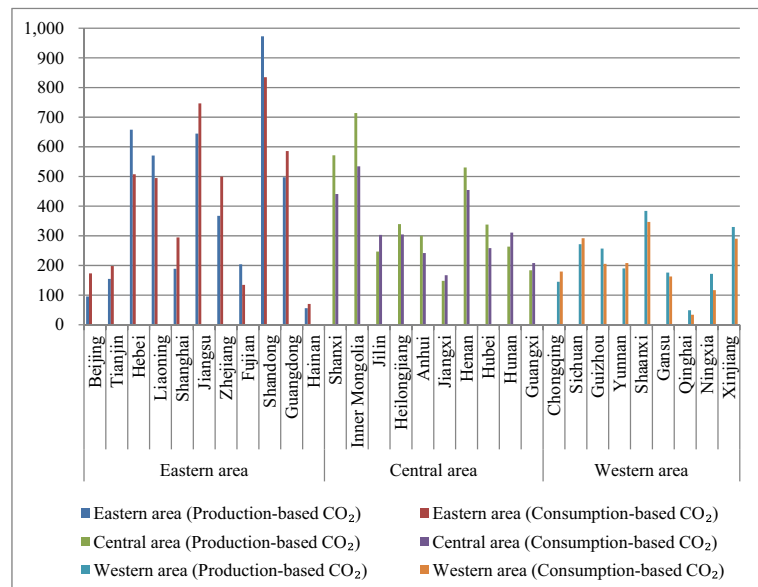
regions are situated in the central and western areas with lower economic development levels. These emission-exporting regions produce products to meet the final demands of themselves and other regions and thus also lead to large amounts of CO_2 emissions in other regions. It is interesting that consumption-based CO_2 emissions are usually higher than production-based CO_2 emissions in the eastern developed regions in China, whereas the production-based CO_2 emissions are higher than consumption-based CO_2 emissions in less developed regions, especially in the central and western areas. Similar results are also found in Mi et al. (2017).

Energy efficiency and CO_2 emission efficiency

By employing the combined approach of EEIO model and SBM model, energy efficiency and CO_2 emission efficiency with the data on consumption-based CO_2 emissions can be obtained. The results are reported in columns (4) and (6) in Table 2. To illustrate the rationality of the proposed approach, the efficiency results with the data obtained from the production perspective is also presented, as shown in columns (3) and (5) in Table 2.

With the data on consumption-based CO_2 emissions, as shown in Table 2, energy efficiency varies from 0.1453 to 1, with an average of 0.6465. It is found that six regions are deemed as efficient in energy efficiency, i.e., Beijing, Tianjin, Shanghai, Yunnan, Liaoning, and Fujian, and other regions are estimated to be inefficient.

More than 14 regions, including the above six efficient regions, have high energy efficiency scores which are all higher than 0.7. Most of these regions are located in the eastern area, and benefit from the relatively high government investments and advanced energy saving and production technologies. Additionally, the manufacturing activities have been transferred to inland areas due to increasing costs of labor, land and environmental restrictions in these regions in recent years. In contrast, 12 regions, namely Inner Mongolia, Hebei, Shanxi, Ningxia, Guizhou, Xinjiang, Shaanxi, Heilongjiang, Qinghai, Gansu, Jilin, and Hainan, are found to be suffered from lower energy efficiency scores less than 0.5. All these regions are situated in the central and western areas in China except Hainan.

With regard to CO_2 emission efficiency, the results demonstrate that most regions in China perform inefficiently in CO_2 emissions. The efficiency varies from 0.2279 to 1, with an average score of 0.5730. Note that the efficiency scores and rankings of regions are similar to those of energy efficiency. It is interesting that mean energy efficiency are larger than that of CO_2 emission efficiency under both principles (i.e., production-based and consumption-based principles) as shown in Table 2, i.e., 0.6041 vs. 0.5890 and 0.6465 vs. 0.5730, respectively. This indicates that Chinese regions tend to experience higher energy efficiency than CO_2 emission efficiency. In order to examine whether or not energy efficiency and CO_2 emission efficiency have significant difference under production-based principle or

Table 2 Results of energy efficiency, CO_2 emissions efficiency, and abatement costs

Group	Regions	Energy efficiency		CO_2 emission efficiency		Abatement costs (CNY/ton)	
		Production	Consumption	Production	Consumption	Production	Consumption
Emission-importing regions	Beijing	1.0000	1.0000	1.0000	1.0000	27.6275	347.1929
	Tianjin	1.0000	1.0000	1.0000	1.0000	51.1580	15.5006
	Jilin	0.3369	0.3369	0.2961	0.3637	128.0771	122.7798
	Shanghai	1.0000	1.0000	1.0000	1.0000	8.4650	12.1880
	Jiangsu	0.6385	0.6385	0.5888	0.6315	202.4668	222.7633
	Zhejiang	0.9666	0.9666	0.9561	0.6345	166.5370	124.0304
	Jiangxi	0.5551	0.5551	0.4675	0.7497	292.0618	258.1628
	Hunan	0.8967	0.8967	0.8695	0.4869	280.3193	237.4768
	Guangdong	0.9600	0.9690	0.9586	0.7707	298.1556	310.1983
	Guangxi	0.5829	0.7340	0.5538	0.4280	223.4291	208.7775
	Hainan	0.4491	0.4491	0.5298	0.2778	170.8117	135.5110
	Chongqing	0.7733	0.8174	0.7615	0.4346	253.9626	211.9901
	Sichuan	0.7276	0.8950	0.7066	0.5589	260.6118	272.6260
	Yunnan	1.0000	1.0000	1.0000	1.0000	80.1147	95.1580
	Mean	0.7776	0.8042	0.7634	0.6669	174.5570	183.8825
Emission-exporting regions	Hebei	0.3228	0.4354	0.2892	0.3579	131.3371	174.5774
	Shanxi	0.4621	0.4621	0.4870	0.5469	70.6699	91.5447
	Inner Mongolia	0.1453	0.1453	0.1187	0.2878	74.1679	99.0957
	Liaoning	1.0000	1.0000	1.0000	1.0000	23.0051	141.8398
	Heilongjiang	0.4183	0.4183	0.4170	0.3072	134.4323	149.8642
	Anhui	0.8370	0.8370	0.8344	0.9805	176.7807	194.8751
	Fujian	1.0000	1.0000	1.0000	1.0000	65.8945	555.0537
	Shandong	0.3888	0.5353	0.3585	0.4094	149.9748	199.7139
	Henan	0.3577	0.5977	0.3012	0.4453	161.7588	217.2158
	Hubei	0.7054	0.7054	0.6813	0.5885	219.6462	287.0476
	Guizhou	0.2951	0.2951	0.2757	0.2279	88.8819	111.1739
	Shaanxi	0.2341	0.3880	0.2053	0.2846	107.9120	138.8216
	Gansu	0.1934	0.3259	0.1713	0.2368	107.0196	115.5150
	Qinghai	0.2638	0.3780	0.2575	0.3834	127.3913	187.0290
	Ningxia	0.3391	0.3391	0.3134	0.4001	45.4755	66.9714
	Xinjiang	0.2739	0.2739	0.2727	0.3972	75.8565	86.1822
	Mean	0.4523	0.5085	0.4364	0.4909	110.0128	176.0326
	Overall mean	0.6041	0.6465	0.5890	0.5730	140.1334	179.6959

consumption-based principle, the Mann–Whitney U test is used. The test results are reported in Table 3.

According to Table 3, the hypothesis that there is no difference between energy efficiency and CO_2 emission efficiency cannot be rejected under both principles. This indicates that regional energy efficiency may have a positive relationship with CO_2 emission efficiency.

Notably, there exist great disparities in energy efficiency between two groups. In particular, emission-importing regions always experience higher energy efficiency scores than emission-exporting regions under each principle. Such differences can be interpreted by the differences in factor endowments and technological and economic levels across various regions. Since most regions in emission-importing group are located in the

Table 3 Results of Mann–Whitney U test regarding both principles

Measure	Null hypothesis (H0)	Mann-Whitney U	p value
Production-based	Median (energy efficiency)= Median (CO_2 emission efficiency)	432	0.7893
Consumption-based	Median (energy efficiency)= Median (CO_2 emission efficiency)	387	0.3497

eastern area, their economic developments exhibit superior performance over the inland regions. Moreover, the geographic concentration of economic activities in the eastern regions further enhances the productivity growth in the eastern regions, which further take advantageous effect on energy efficiency. It is noteworthy that, even within the group of emission-importing regions, there are still some regions exhibiting poor energy performance. To be specific, Jilin is ranked at the bottom of energy efficiency score (i.e., 0.3369) of all regions within the group. We further conduct Mann–Whitney U test to examine whether or not there are significant differences in terms of energy efficiency between the two groups. Table 4 reports the test results.

Table 4 shows that the difference of energy performance between the net imports and net exports is statically significant (at 1% significant level) under each principle. This indicates that emission-importing regions always exhibit higher energy efficiency scores than emission-exporting regions.

Note in Table 2 that mean energy efficiency from the consumption perspective is larger than that from the production perspective in both emission-importing group and emission-exporting group, i.e., 0.8042 vs.

0.7776 and 0.5085 vs. 0.4523, respectively. This may imply that neglecting the emissions caused by final consumptions may underestimate energy efficiency in China. To be specific, energy efficiency of Guangdong, Chongqing, Guangxi, Sichuan, Hebei, Shandong, Henan, Shaanxi, Qinghai, and Gansu show an increase trend when consumption-based principle is adopted, while other regions remain unchanged. Similarly, regarding CO_2 emission efficiency, those emission-importing regions are estimated to have higher efficiency scores, while those emission-exporting regions perform poorly. We also find that mean CO_2 emission efficiency of emission-importing regions decrease from 0.7634 to 0.6669 when consumption-based measurement is employed. Nevertheless, the emission-exporting regions enjoy a slight increase from 0.4364 to 0.4909 in the efficiency when considering the consumption-based data instead of production-based one.

Abatement costs of CO_2 emissions

Based on Eqs. (8) and (9), CO_2 emission abatement costs of 30 regions are obtained and shown in columns

Table 4 Results of Mann–Whitney U test regarding two groups of regions

Index	Measure	Null hypothesis (H0)	Mann–Whitney U	p value
Energy efficiency	Production-based	Median (emission-importing regions) = median (emission-exporting regions)	42	0.0035***
	Consumption-based	Median (emission-importing regions) = median (emission-exporting regions)	46	0.0059***
CO_2 emission efficiency	Production-based	Median (emission-importing regions) = median (emission-exporting regions)	42	0.0035***
	Consumption-based	Median (emission-importing regions) = median (emission-exporting regions)	61	0.0333**
Abatement costs	Production-based	Median (emission-importing regions) = median (emission-exporting regions)	66	0.0558*
	Consumption-based	Median (emission-importing regions) = median (emission-exporting regions)	91	0.3827

Note: ***, **, and * denote the 1%, 5, and 10% significance level, respectively

(7) and (8) in Table 2. We find that China's regions should pay, on average, 179.6956 CNY to reduce one ton of CO_2 emissions from the consumption perspective. Note that the abatement costs of CO_2 emissions fluctuate within a range from 555.0537 CNY/ton to 12.1880 CNY/ton. In particular, Shanghai, Tianjin, Ningxia, Xinjiang, Shanxi, Yunnan, and Inner Mongolia are estimated to achieve relatively low abatement costs of CO_2 emissions, which are lower than 100 CNY/ton. The costs of other regions, such as Jiangxi, Sichuan, Hubei, Guangdong, Beijing, and Fujian, are estimated to be larger than 250 CNY/ton. These results imply that that there are significant differences in terms of CO_2 emissions in China. Thus, it is unreasonable to set a uniform carbon reduction targets for different regions due to the differences in the opportunity costs to abate carbon emissions.

Table 2 shows that mean shadow price estimated under the consumption-based principle is higher than the current international market price of carbon emission trading. In the EU market, the average price is about 8.12€ per ton of CO_2 emissions in 2012. In the context of China, Wang and Wei (2014) find that the average industrial CO_2 emission abatement costs for Chinese major cities is 45$ during 2006–2010. In the study of Zhang et al. (2014), the abatement costs of CO_2 emissions at provincial levels in China vary from 7.46 CNY/ton to 184.99 CNY/ton in 2012. These findings can support our results regarding the abatement costs of CO_2 emissions.

With regard to the described two groups, we find that CO_2 emission shadow price on average of emission-exporting regions is lower than emission-importing regions. In line with the basic principle of environmental economics, marginal abatement costs of CO_2 emission are positively related with CO_2 emission efficiency and environmental regulation within a region. The extant literature (Choi et al. 2012; Wang et al. 2017) also documents that higher efficiency in a region will lead to higher marginal CO_2 abatement costs. As shown in Table 2, CO_2 emission efficiency scores of emission-importing regions are indeed higher than those of emission-exporting regions.

Notably, emission-importing group shows a higher CO_2 emission abatement costs under the consumption-based measurement than production-based measurement, i.e., 183.8825 CNY/ton vs. 174.5570 CNY/ton. Under the consumption-based approach, as the net emissions for the whole nation are trimmed, the abatement costs of CO_2 emissions will accordingly increase, even if the real consumption of CO_2 emissions in these regions are rising with the consumption-based measure. Regarding emission-

exporting regions, they gain mean CO_2 emission abatement costs 176.0326 CNY/ton, which is much larger than that found by Choi et al. (2012) from the production-based perspective (i.e., 110.0128 CNY/ton). Therefore, it can be inferred that ignoring consumption-based CO_2 emissions will underestimate the CO_2 emission abatement costs in China.

To examine the difference between the two groups in terms of CO_2 emission abatement costs, Mann–Whitney U test is further used, and the results are also reported in Table 4. Clearly, the null hypothesis in terms of abatement costs from the production-based perspective can be rejected at the significant level of 10%. This indicates that there exists group-heterogeneity between emission-importing regions and emission-exporting regions. However, the null hypothesis cannot be rejected when consumption-based CO_2 emissions are considered, which suggests that no significant difference regarding abatement costs can be found between the two groups.

Robustness check

To further test the robustness of our results, we re-conduct our analysis by using the dataset in 2007. This is because the input–output tables at regional level in China are published every 5 years. By far, only the latest tables in 2007 and 2012 are available. The check results with respect to CO_2 emissions show that total CO_2 emissions are 7324.97 Mt and 6855.03 Mt in 2007, respectively, and these emissions increase to 10,016.25 Mt and 9598.85 Mt in 2012, respectively. Specifically, four regions, i.e., Heilongjiang, Hubei, Shaanxi, and Qinghai, are regarded as emission-importing regions in 2012, while are found to be emission-exporting regions in 2007. By contrast, two net exporters (i.e., Guangdong and Sichuan) in 2007 become net importers in 2012.

Notably, we find that energy efficiency, carbon efficiency and abatement costs show upward trends during the study period, regardless of whether or not the consumption-based emissions are considered. Nevertheless, we find that the main findings and insights remain unchanged when the dataset changes. To be specific, CO_2 emission efficiency will decrease for net emission importers, while increase in net emission exporters. As for energy efficiency and CO_2 emission abatement costs, both groups exhibit increasing trends when consumption-based emissions are considered.

Conclusions and policy implications

The potential transferring of embodied carbon through interregional and international trades will lead to significant biased results of carbon emission estimation. This is attributed to the practice that embodied carbon is generally emitted when products are consuming. In such a context, a challenge is emerging that energy efficiency, CO_2 emission efficiency and related abatement costs should be reconsidered. This paper attempts to address such issues in the context of China's regions by using the dataset in 2012. To this end, we first use EEIO model to calculate the consumption-based CO_2 emissions, and then an improved SBM model to evaluate energy efficiency, CO_2 emission efficiency and related abatement costs. In the analysis, 30 regions can be classified into two groups according to the estimation results of CO_2 emissions under the two principles. In particular, a region is defined as an emission-importing region when the consumption-based CO_2 emissions are higher than the production-based emissions; otherwise, it is an emission-exporting region. We also present the results obtained based on the approach proposed by Choi et al. (2012) from traditional production-based perspective.

Results of the application reveal the following findings and conclusions. First, with respect to energy efficiency and CO_2 emission efficiency, there are significant group-heterogeneity between two groups. On average, the emission-importing regions always have relatively higher energy and CO_2 emission efficiencies under both principles. We also find that energy efficiencies of both groups under the consumption-based principle are higher than those under the production-based principle. Surprisingly, we find that CO_2 emission efficiency of emission-exporting regions experience a slight increase whereas the emission-importing regions suffer from a decrease when the dataset changes from the production-based perspective to the consumption-based perspective. Second, regarding CO_2 emission abatement costs, no significant difference between two groups can be found under the consumption-based perspective. Mean CO_2 emissions shadow price of emission-exporting regions are lower than the emission-importing regions. The abatement costs for CO_2 emissions become more difficult for net exporters due to the decline in total carbon emissions from the consumption perspective. It is noteworthy that the group of net importers still encounters an increase in abatement costs when the production-based perspective changes to the consumption-based perspective.

According to our findings, some important policy implications are achieved. First, accounting principles of regional CO_2 emissions have significant effects on their energy efficiency, CO_2 emission efficiency and associated abatement costs. The governments would be cautious only from the production-based principle when making energy policies or CO_2 emission control policies, especially for those emission-intensive regions such as Inner Mongolia, Hebei, Shandong and Shanxi. Generally speaking, more strict energy saving and emission reduction policies should be imposed on these regions. However, large amounts of emissions generated from these provinces are caused by the final consumptions of products traded from other developed regions. Thus, those developed regions should take more responsibility for carbon reductions. Second, policies and plans should be put into practice based on local conditions due to the great disparities in efficiency and abatement costs of CO_2 emissions across regions. In particular, well-developed regions evidence better energy and emission performance than underdeveloped regions.

Notably, there are still several issues that can be further addressed in future research. First, this study calculates CO_2 emissions from the consumption-based perspective by employing the single-regional input–output model. It is hard to track footprints of carbon emissions in the process of interregional trade. Thus, it is necessary to adopt multi-regional input–output table of China to further conduct the analysis. Second, the uncertainties in the data regarding the input–output table and emission factors will affect the estimation accuracy of CO_2 emissions. It is interesting to examine the impact of the uncertainty on the results in our work. Third, this study is conducted just using the dataset in 2012 and further checked by using the dataset in 2007. It is imperative for further investigating the dynamic energy efficiency, CO_2 emission efficiency and related abatement costs of CO_2 emissions with a long-time span dataset.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

Appendix

Table 5 Sectors for provincial IOTs and corresponding energy consumption

No.	Sectors	Sectors in IOTs
1	Agriculture	(1) Agriculture
2	Coal mining and washing	(2) Coal mining and washing
3	Petroleum and natural gas extraction	(3) Petroleum and natural gas extraction
4	Metal mining and dressing	(4) Metal mining and dressing
5	Non-metal and other mineral mining and dressing	(5) Non-metal and other mineral mining and dressing
6	Food processing and tobaccos processing	(6) Food processing and tobaccos processing
7	Textile industry	(7) Textile industry
8	Manufacture of leather, fur, feather and related products	(8) Manufacture of leather, fur, feather and related products
9	Timber processing and furniture manufacturing	(9) Timber processing and furniture manufacturing
10	Papermaking, printing, cultural, educational and sports articles	(10) Papermaking, printing, cultural, educational and sports articles
11	Petroleum processing, coking, and nuclear fuel processing	(11) Petroleum processing, coking, and nuclear fuel processing
12	Chemical industry	(12) Chemical industry
13	Non-metal mineral products	(13) Non-metal mineral products
14	Smelting and pressing of metals	(14) Smelting and pressing of metals
15	Metal products	(15) Metal products
16	General machinery	(16) General machinery
17	Specialist machinery	(17) Specialist machinery
18	Transportation equipment	(18) Transportation equipment
19	Electric equipment and machinery	(19) Electric equipment and machinery
20	Electronic and telecommunications equipment	(20) Electronic and telecommunications equipment
21	Instrument and meter	(21) Instrument and meter
22	Other manufacturing industry	(22) Other manufacturing industry
23	Waster and flotsam	(23) Waster and flotsam
24	Repair service for metal products, machinery and equipment	(24) Repair service for metal products, machinery and equipment
25	Electricity and hot water production and supply	(25) Electricity and hot water production and supply
26	Gas production and supply	(26) Gas production and supply
27	Water production and supply	(27) Water production and supply
28	Construction	(28) Construction
29	Transport, storage and post	(30) Transport, storage and pose
30	Wholesale and retail trade, hotels and catering services	(29) Wholesale and retailing; (31) Hotel and restaurant
31	Other service industries	(32) Information Transmission, Computer services and Software; (33) Finances; (34) Real state; (35) Leasing and commercial services; (36) Research and Experimental Development; (37) Water conservancy, Environment and Public Facilities Management; (38) Service to Households and Other Service; (39) Education; (40) Health, Social Security and Social Welfare; (41) Culture, Sports and Entertainment; (42) Public Management and Social Organization

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