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Determinants of changes in electricity generation intensity among different power sectors

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Abstract: This study analyzes the determinants of changes in electricity generation intensity in China and further uncovers the reasons for the differences between the changes in electricity generation intensity in the thermal and sustainable power sectors. By developing a factorial-intertemporal nested decomposition technique using the refined Laspeyres index, we demonstrate the contributions of electricity generation structure, electricity generation-to-consumption ratio, production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity effects. Although the electricity generation intensity of the thermal power sector has been lower than that of the sustainable power sector, the latter has declined remarkably and has remained the key sector driving the overall changes in electricity generation intensity. Meanwhile, the effect of electricity consumption intensity is the main factor that reduces electricity generation intensity. Moreover, the impact of production electricity consumption intensity in the

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thermal power sector exceeds its impact in the sustainable power sector. Ultimately, we find that the differences between the changes in electricity generation intensity in the thermal and sustainable power sectors are mainly due to their differences in production electricity consumption intensity.
Keywords: Power sector; Electricity generation intensity; Refined Laspeyres index; Nested decomposition; China.

1. Introduction

Electricity plays an increasingly important role in economic growth and in humans' daily lives (Buceti, 2014; Halkos and Polemis, 2018; Sony and Mekoth, 2018). Over the last three decades, the global power generation capacity had increased by 2.6 times—from 9830.26 TWh in 1985 to 25551.30 TWh in 2017 (BP, 2016; BP, 2018). The dramatic increase in electricity generation has not only helped the economies of most countries to develop steadily (Polemis and Dagoumas, 2013; Atems and Hotaling, 2018), but has also enhanced the quality of life in these countries (Pachauri, 2014; Aklin et al., 2016). A stable electricity supply is vital for every country's sustainable economic growth and the steady improvement of human well-being (Contreras et al., 2003; Malekpoor et al., 2017; Liu et al., 2018).

As electricity generation itself consumes natural resources and energy (the latter of which is generally non-renewable in the short term), environmental problems—especially greenhouse gas emission and atmospheric pollution—are inherent in electricity generation (Yan et al., 2018; Baležentis et al., 2019). Therefore, a stable electricity supply requires the sustainable growth of economic efficiency in the power sector. The term *electricity generation efficiency* refers to the extent to which electricity is produced economically. Like the concepts of carbon intensity, which reflects carbon emission efficiency (Rodrígueza and Pena-Boquete, 2017; Pretis and Roser, 2017), and energy intensity, which reflects energy consumption efficiency (Shahiduzzaman and Alam, 2013; Mahmood and Ahmad, 2018), electricity generation intensity can be used to measure electricity generation efficiency. The greater the economic output driven by a unit of electricity generation or the lower the electricity generation needed to produce a unit of economic output, the higher the electricity generation efficiency and the lower the electricity generation intensity are. Given the global consensus on green and sustainable development, it is necessary to discuss the economic efficiency of the power sector and uncover the driving forces behind changes in electricity generation intensity, especially in developing countries.

At the beginning of their economic development, countries tend to choose their own resource-endowed power systems (usually coal-fired). At this time, the use of the relatively backwards technology and barriers to transnational technology transfer lead to severe electricity loss during generation, transmission, distribution, and storage in these countries; furthermore, it is difficult for the renewable power sector to become competitive (Chen et al., 2018b; Atems and Hotaling, 2018). As the largest developing country and electricity producer in the world, China has a crucial impact on global electricity generation, especially in terms of electricity generation structure and efficiency and power sector competitiveness. Previous data have shown that China's electricity generation capacity reached 6495.10 TWh in 2017, accounting for 25.42% of the world's electricity generation, of which 70.39% was generated by fossil fuels (BP, 2018). Thus, the purpose of this paper is to analyze the determinants of changes in electricity generation intensity and further uncover the reasons for differences in the changes in electricity generation intensity of different sectors in the context of China.

Previous studies have aimed to solve three key issues associated with electricity generation intensity. The first is how to choose a power system and structure. Globally, thermal power from coal-fired, hydro, nuclear, and biomass systems remains the dominant form of electricity generation in most countries, accounting for 64.66% of the world's electricity generation by 2017; in particular, coal-fired electricity generation accounted for 38.05% (BP, 2018). Whether to maintain the current power system or to choose a new generation structure has emerged as an urgent issue for policymakers. Continuing to rely on increasingly scarce fossil fuels for electricity generation will not only lead to the gradual depletion of these natural resources but also result in increasingly severe environmental pollution and greenhouse gas emissions (Ahmad et al., 2017; Yan et al., 2018; Baležentis et al., 2019). However, choosing new electricity generation forms, such as encouraging the use of renewable energy, may not only result in uneconomical electricity generation due to unfavorable resource endowment and immature technology but also entails the risk of slow acceptance by the public (Streimikiene et al., 2016; Rehdanz et al., 2017; Ozcan, 2019).

The second issue addressed in earlier work is the promotion of economic efficiency in the power sector. Although a stable and low-cost electricity supply is conducive to productive and consumptive activities, attracts public and private investments (Payne, 2010), and is a necessary input to economic growth, improving the economic efficiency of the power sector is not easy. The speed at which power systems can be updated, the cover rate of the grid, the refurbishment frequency of generation infrastructure, and the stability of consumption sources directly determine the economic efficiency of the power sector (Szabó et al., 2016). Higher electricity generation costs inhibit investment and weaken competition, acting as a bottleneck for economic growth and reducing economic performance (Di Bella and Grigoli, 2017). To feasibly fulfill the goals of economic growth, investment expansion, job creation, energy conservation, and emissions reduction, as well as to supply electricity to rural and remote areas, power sectors with lower-cost and higher-efficiency electricity generation must be developed (Reddy, 2018).

The third problem that is often debated is how to treat the competition–development nexus in the power sector, a discussion that is an extension of the above two issues. Competition and development within power sectors originates from electricity generation diversity. The fossil fuel-fired power sector has usually been considered to be more competitive in the marketplace. Soto and Vergara (2014) and Chen et al. (2018a) have shown that technological innovation can continually improve the efficiency of electricity generation, thereby maintaining the market competitiveness of the thermal power sector. Meng et al. (2016) showed that the implementation of market-oriented reform could not only improve the efficiency of the thermal power sector, but also improve its market competitiveness. Chen et al.

(2018b) argued that it is unrealistic for developing countries to rapidly change their energy structure, especially in the power sector, where traditional thermal power will not decline prematurely and be replaced by emerging sustainable power. Even so, the market competitiveness of the sustainable power sector cannot be ignored. Wind power's extremely low operating costs led Vogel et al. (2018) to argue that wind power costs are nearly zero compared with other power sectors; in recent years, the wind power sector has developed rapidly in some countries and, in the long run, wind power will occupy a competitive position and play an important role in the electricity market. Electricity generation from sustainable sources such as biomass, solar, and wind power, helps to improve the safety of the ecological system. More importantly, such resources are abundant in nature and easy to deploy (Reddy, 2018). Therefore, if supported by policymakers, the sustainable power sector will develop rapidly with cost and technology advantages, thereby gaining a competitive edge over the thermal power sector.

Although extensive research has sought to solve the problems surrounding the form, structure, and economic efficiency of electricity generation, as well as competition and development within power sectors, most studies have not focused on the economic output driven by electricity generation and the reasons for the differences across power sectors. The contributions of this paper are twofold. First, we try to measure electricity generation efficiency and market competitiveness using electricity generation intensity, considering both electricity production and consumption. Although numerous studies have evaluated the efficiency and market competition of power sectors in terms of technical, energy, and emissions efficiency (Johnstone et al., 2017; Dahlke, 2018), it is not easy to compare sectors directly because of their different evaluation processes and objectives. To some extent, policymakers focus more on whether economic output could be driven by a unit of electricity generation than which process that efficiency improvement comes from. This policy objective can simply be reflected by electricity generation intensity. Furthermore, most previous studies have not simultaneously discussed the issues of electricity production and consumption (Apergis and Payne, 2012; Al-mulali et al., 2014; Halkos and Tzeremes, 2014), despite the close relationship between them. Electricity generation behavior can affect electricity consumption decision-making, and the latter has a significant reverse impact on the former (Atems and Hotaling, 2018). Therefore, it is reasonable to link electricity production and consumption when exploring the determinants of electricity generation intensity in different power sectors.

Second, to find nested effects that directly impact changes in electricity generation intensity and obtain impacts from different periods, we develop a factorial-intertemporal nested decomposition technique using the refined Laspeyres index (RLI). Since index decomposition analysis (IDA) was proposed, various types of IDA—especially RLI and logarithmic mean Divisia index (LMDI) decomposition methods—have been widely used to analyze the determinants of changes in certain variables (Ang and Zhang, 2000). However, no method yet proposed has perfectly solved the nested decomposition problem (Chen et al., 2017b; Chen et al., 2018b; Chen et al., 2018c), which makes it impossible to discuss indirect influences from nested effects on electricity generation (González and Moreno, 2015; Sumabat et al., 2016; Yan et al., 2018). This paper attributes the changes in electricity generation intensity to electricity consumption, which is influenced by production electricity consumption, residential electricity consumption, and electricity consumption loss. Thus, it is necessary for us to develop a new decomposition technique. In addition to factorial nested decomposition, intertemporal nested decomposition is also important because different trends in the electricity generation intensity of different power sectors exist in different periods.

2. Methodology

2.1. RLI decomposition analysis

In this study, we employ RLI decomposition, a form of IDA (Ang et al., 1998), to uncover the determinants of changes in electricity generation intensity. To apply RLI decomposition, we first transform a variable into some relative effects which are multiply formatted under the IDA identity principle; second, we can attribute the changes in this variable to those accumulated effects; finally, we can calculate the impact of each effect under the "jointly created and equally distributed" principle (Sun, 1998).

As a method that has been widely used in discussions of the determinants of the changes in greenhouse gas emissions, energy, fuel and natural resources consumption, and policy pressures (Table 1), RLI decomposition has several advantages over other decomposition methods. First, it can achieve complete decomposition (Sun, 1998). Second, it satisfies the time-reversal, factor-reversal, and zero-value robust properties tests (Ang and Zhang, 2000). Third, it is simple and robust, and has a clear economic meaning (Chen et al., 2017a).

[Insert Table 1 here.]

Nevertheless, RLI decomposition has several drawbacks; most notably, it does not solve nested decomposition. Although some studies have tried to use LMDI decomposition for this purpose, the problem has not been perfectly overcome. For example, although Chen et al. (2017b) used RLI decomposition to decompose the multiplicative form of LMDI decomposition, the results of the two decompositions were not directly comparable, owing to the mixture of the two decomposition methods. Meanwhile, this kind of processing cannot be applied to the additive form of LMDI decomposition. Although the first-order Taylor expansion technique used by Chen et al. (2018c) to decompose the additive form of LMDI decomposition into nested factors, it lost the inherent advantage of achieving complete decomposition. Although Chen et al. (2018d) completely decomposed the nested factors of the additive form of LMDI decomposition by adjusting the logarithmic mean weights, they lost the unique weight function, and the nonuniform logarithmic mean weights make it impossible to directly compare the influences of driving factors.

Here, we try to solve nested decomposition in the framework of RLI decomposition. As mentioned above, electricity generation intensity can be used to reflect the economic efficiency of electricity generation, which is usually related to the electricity generation form and consumption. Thus, the electricity generation intensity may relate to the electricity generation structure and consumption intensity. The IDA identity used in this paper to uncover the factors affecting electricity generation intensity is shown below:

$$EGI = \frac{EG}{Y} = \sum_j \frac{EG_j}{EG} \cdot \frac{EG}{EC} \cdot \frac{EC}{Y}, \qquad (1)$$

where EG represents electricity generation; Y represents economic output; EC represents electricity consumption; and j represents the jth generation form, including thermal, hydro, nuclear, wind, and solar electricity generation. Other than thermal power, which depends on fossil fuels (especially coal), the other electricity generation forms are clean and sustainable. Therefore, in the following analysis, we will mainly compare the electricity generation intensity of thermal and sustainable power sectors and their determinants. To simplify (1), we express it in the following form:

$$EGI = \sum_j EGS_j \cdot EGC \cdot ECI . \qquad (2)$$

The larger the EGI, the lower the economic output driven by a unit of electricity generation, indicating a decrease in the economic efficiency of electricity generation. $EGS_j = EG_j / EG$. The larger the EGS_j, the higher the proportion of electricity generated by the jth generation form and the higher the dependence on the jth generation form. $EGC = EG/EC$. $EGC > 1$ indicates net electricity generation, i.e., generation exceeds consumption. The larger the EGC, the stronger the net electricity generation capacity. Conversely, $EGC < 1$ indicates net electricity consumption, i.e., consumption exceeds generation. The smaller the EGC, the stronger the net electricity consumption capacity. $ECI = EC/Y$. The larger the ECI, the greater the electricity consumption per unit of economic output and the lower the efficiency of electricity consumption.

EGI^t and EGI^b represent the electricity generation intensities of the reporting and base periods, respectively, as follows:

$$EGI^t = \sum_j EGS_j^t \cdot EGC^t \cdot ECI^t , \qquad (3)$$

$$EGI^b = \sum_j EGS_j^b \cdot EGC^b \cdot ECI^b \ . \qquad (4)$$

Then, changes in EGI can be expressed as

$$\Delta EGI = EGI^t - EGI^b = \sum_j EGS_j^t \cdot EGC^t \cdot ECI^t - \sum_j EGS_j^b \cdot EGC^b \cdot ECI^b \ . \qquad (5)$$

Using the procedures proposed by Sun (1998), Dhakal (2009), and Chen et al. (2017b), we obtain the following formula:

$$\Delta EGI = \Delta EGI_{egs} + \Delta EGI_{egc} + \Delta EGI_{eci} , \qquad (6)$$

where ΔEGI_{egs}, ΔEGI_{egc}, and ΔEGI_{eci} represent the impacts of electricity generation structure, electricity generation-to-consumption ratio, and electricity consumption generation intensity respectively, as follows:

$$\begin{aligned}\Delta EGI_{egs} &= \sum_j \left(EGS_j^t - EGS_j^b\right)\cdot EGC^b \cdot ECI^b \\ &+\frac{1}{2}\sum_j \left(EGS_j^t - EGS_j^b\right)\cdot\left(EGC^t - EGC^b\right)\cdot ECI^b \\ &+\frac{1}{2}\sum_j \left(EGS_j^t - EGS_j^b\right)\cdot EGC^b \cdot\left(ECI^t - ECI^b\right) \\ &+\frac{1}{3}\sum_j \left(EGS_j^t - EGS_j^b\right)\cdot\left(EGC^t - EGC^b\right)\cdot\left(ECI^t - ECI^b\right)\end{aligned} \qquad (7)$$

$$\begin{aligned}\Delta EGI_{egc} &= \sum_j \left(EGC^t - EGC^b\right)\cdot EGS_j^b \cdot ECI^b \\ &+\frac{1}{2}\sum_j \left(EGC^t - EGC^b\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot ECI^b \\ &+\frac{1}{2}\sum_j \left(EGC^t - EGC^b\right)\cdot EGS_j^b \cdot\left(ECI^t - ECI^b\right) \\ &+\frac{1}{3}\sum_j \left(EGC^t - EGC^b\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot\left(ECI^t - ECI^b\right)\end{aligned} \qquad (8)$$

$$\begin{aligned}\Delta EGI_{eci} &= \sum_j \left(ECI^t - ECI^b\right)\cdot EGS_j^b \cdot EGC^b \\ &+\frac{1}{2}\sum_j \left(ECI^t - ECI^b\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot EGC^b \\ &+\frac{1}{2}\sum_j \left(ECI^t - ECI^b\right)\cdot EGS_j^b \cdot\left(EGC^t - EGC^b\right) \\ &+\frac{1}{3}\sum_j \left(ECI^t - ECI^b\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot\left(EGC^t - EGC^b\right)\end{aligned} \qquad (9)$$

2.2. Two-step nested decomposition analysis with RLI decomposition

Regardless of the inevitable loss that occurs during electricity consumption, the production and residential sectors consume electricity together, as shown below:

$$EGC = EC^{prod} + EC^{resi} + EC^{loss}, \qquad (10)$$

where EC^{prod}, EC^{resi}, and EC^{loss} represent the production electricity consumption, residential electricity consumption, and electricity consumption loss, respectively. By substituting Eq. (10) into Eq. (1), we get

$$\frac{EG}{Y} = \sum_j \frac{EG_j}{EG} \cdot \frac{EG}{EC} \cdot \frac{\left(EC^{prod} + EC^{resi} + EC^{loss}\right)}{Y} \qquad (11)$$

$$\begin{aligned} EGI &= \sum_j EGS_j \cdot EGC \cdot \left(ECI^{prod} + ECI^{resi} + ECI^{loss}\right) \\ &= \sum_j EGS_j \cdot EGC \cdot ECI^{prod} + \sum_j EGS_j \cdot EGC \cdot ECI^{resi} \\ &+ \sum_j EGS_j \cdot EGC \cdot ECI^{loss} \end{aligned} \qquad (12)$$

where $ECI^{prod} = EC^{prod} / Y$, $ECI^{resi} = EC^{resi} / Y$, and $ECI^{loss} = EC^{loss} / Y$ represent the production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity, respectively.

Further, the change in electricity generation intensity can be described as follows:

$$\Delta EGI = \Delta EGI_{egs} + \Delta EGI_{egc} + \Delta EGI_{ecip} + \Delta EGI_{ecir} + \Delta EGI_{ecil}, \qquad (13)$$

where ΔEGI_{ecip}, ΔEGI_{ecir}, and ΔEGI_{ecil} represent the impact of production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity respectively, as follows:

$$\begin{aligned} \Delta EGI_{ecip} &= \sum_j \left(ECI^{prodt} - ECI^{prodb}\right) \cdot EGS_j^b \cdot EGC^b \\ &+ \frac{1}{2}\sum_j \left(ECI^{prodt} - ECI^{prodb}\right) \cdot \left(EGS_j^t - EGS_j^b\right) \cdot EGC^b \\ &+ \frac{1}{2}\sum_j \left(ECI^{prodt} - ECI^{prodb}\right) \cdot EGS_j^b \cdot \left(EGC^t - EGC^b\right) \\ &+ \frac{1}{3}\sum_j \left(ECI^{prodt} - ECI^{prodb}\right) \cdot \left(EGS_j^t - EGS_j^b\right) \cdot \left(EGC^t - EGC^b\right) \end{aligned} \qquad (14)$$

$$\begin{aligned} \Delta EGI_{ecir} &= \sum_j \left(ECI^{resit} - ECI^{resib}\right) \cdot EGS_j^b \cdot EGC^b \\ &+ \frac{1}{2}\sum_j \left(ECI^{resit} - ECI^{resib}\right) \cdot \left(EGS_j^t - EGS_j^b\right) \cdot EGC^b \\ &+ \frac{1}{2}\sum_j \left(ECI^{resit} - ECI^{resib}\right) \cdot EGS_j^b \cdot \left(EGC^t - EGC^b\right) \\ &+ \frac{1}{3}\sum_j \left(ECI^{resit} - ECI^{resib}\right) \cdot \left(EGS_j^t - EGS_j^b\right) \cdot \left(EGC^t - EGC^b\right) \end{aligned} \qquad (15)$$

$$\begin{aligned}\Delta EGI_{ecil} &= \sum_j \left(ECI^{losst} - ECI^{lossb}\right)\cdot EGS_j^b \cdot EGC^b \\ &+\frac{1}{2}\sum_j \left(ECI^{losst} - ECI^{lossb}\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot EGC^b \\ &+\frac{1}{2}\sum_j \left(ECI^{losst} - ECI^{lossb}\right)\cdot EGS_j^b \cdot\left(EGC^t - EGC^b\right) \\ &+\frac{1}{3}\sum_j \left(ECI^{losst} - ECI^{lossb}\right)\cdot\left(EGS_j^t - EGS_j^b\right)\cdot\left(EGC^t - EGC^b\right)\end{aligned} \tag{16}$$

This process is referred to as the first step of RLI nested decomposition. We measure the impacts of the nesting effects on the change in electricity generation intensity. Therefore, we can also refer to it as the RLI factorial nested decomposition.

Further, the changes in thermal and sustainable electricity generation intensities can be expressed as follows:

$$\Delta EGI^{thermal} = \Delta EGI_{egs}^{thermal} + \Delta EGI_{egc}^{thermal} + \Delta EGI_{ecip}^{thermal} + \Delta EGI_{ecir}^{thermal} + \Delta EGI_{ecil}^{thermal} \tag{17}$$

$$\Delta EGI^{sust} = \Delta EGI_{egs}^{sust} + \Delta EGI_{egc}^{sust} + \Delta EGI_{ecip}^{sust} + \Delta EGI_{ecir}^{sust} + \Delta EGI_{ecil}^{sust} \tag{18}$$

The differences in the changes in thermal and sustainable electricity generation intensities can be expressed as follows:

$$\begin{aligned}\Delta^{thermal-sust}\left[\Delta EGI\right] &= \Delta EGI^{thermal} - \Delta EGI^{sust} \\ &= \left(\Delta EGI_{egs}^{thermal} - \Delta EGI_{egs}^{sust}\right) + \left(\Delta EGI_{egc}^{thermal} - \Delta EGI_{egc}^{sust}\right) \\ &+ \left(\Delta EGI_{ecip}^{thermal} - \Delta EGI_{ecip}^{sust}\right) + \left(\Delta EGI_{ecir}^{thermal} - \Delta EGI_{ecip}^{sust}\right) \\ &+ \left(\Delta EGI_{ecil}^{thermal} - \Delta EGI_{ecil}^{sust}\right) \\ &= \left(\Delta^{thermal-sust} EGI_{egs}^{t} - \Delta^{thermal-sust} EGI_{egs}^{b}\right) \\ &+ \left(\Delta^{thermal-sust} EGI_{egc}^{t} - \Delta^{thermal-sust} EGI_{egc}^{b}\right) \\ &+ \left(\Delta^{thermal-sust} EGI_{ecip}^{t} - \Delta^{thermal-sust} EGI_{ecip}^{b}\right) \\ &+ \left(\Delta^{thermal-sust} EGI_{ecir}^{t} - \Delta^{thermal-sust} EGI_{ecir}^{b}\right) \\ &+ \left(\Delta^{thermal-sust} EGI_{ecil}^{t} - \Delta^{thermal-sust} EGI_{ecil}^{b}\right)\end{aligned} \tag{19}$$

where $\Delta^{thermal-sust}\left[\Delta EGI\right]$ represents the differences in the changes in thermal and sustainable electricity generation intensity from the base period to the reporting period. The larger $\Delta^{thermal-sust}\left[\Delta EGI\right]$ is, the greater the differences between the changes in economic efficiency of these two power sectors; this also indicates that the thermal power generation is less competitive than the sustainable power generation. $\Delta^{thermal-sust} EGI_{egs}^{t}$ and $\Delta^{thermal-sust} EGI_{egs}^{b}$ represent the impacts of the changes in electricity generation structure between thermal electricity generation and sustainable electricity generation in the reporting and base periods, respectively. $\Delta^{thermal-sust}EGI_{egc}^{t}$ and $\Delta^{thermal-sust}EGI_{egc}^{b}$ represent the impacts of the changes in the electricity generation-to-consumption ratio between thermal and sustainable electricity generation in the reporting and base periods, respectively. $\Delta^{thermal-sust}EGI_{ecip}^{t}$ and $\Delta^{thermal-sust}EGI_{ecip}^{b}$ represent the impacts of the changes in production electricity consumption intensity between thermal and sustainable electricity generation in the reporting and base period, respectively. $\Delta^{thermal-sust}EGI_{ecir}^{t}$ and $\Delta^{thermal-sust}EGI_{ecir}^{b}$ represent the impacts of the changes in residential electricity consumption intensity between thermal electricity generation and sustainable electricity generation in the reporting and base periods, respectively. $\Delta^{thermal-sust}EGI_{ecil}^{t}$ and $\Delta^{thermal-sust}EGI_{ecil}^{b}$ represent the impacts of the changes in electricity consumption loss intensity between thermal and sustainable electricity generation in the reporting and base periods, respectively (see Appendix A).

This process is referred to as the second step of nested RLI decomposition. We can extract the impacts of all the factors, including nested effects, on the changes in electricity generation intensity between different generation forms during the reporting and base periods. That is, the relative competitiveness differences between generation forms in the electricity market from the base period to the reporting period is the net differences after the superposition of the differences in the reporting period is offset by the superposition of the differences in the base period. Therefore, we can also refer to it as intertemporal nested RLI decomposition.

3. Data

This paper explores the changes in electricity generation intensity at the provincial level in China from 1997 to 2016. The data include electricity generation, economic output, and electricity consumption. To analyze the changes in the electricity generation intensity of different power sectors, we collected electricity generation data from the thermal, hydro, nuclear, wind, and solar sectors, classifying the latter four as sustainable electricity generation forms. Meanwhile, to assess the impacts of electricity consumption intensity on electricity generation intensity changes in different power sectors, we collect data on electricity consumption in the agricultural, forestry, animal husbandry, fishery, industrial, construction, transportation, warehousing, postal, wholesale, retail, accommodation, catering, and residential sectors. We classify all the sectors besides the residential sector as the production sector.

All data concerning electricity production and consumption were obtained from the China Energy Statistics Yearbook (NBSPRC, 2017a). Economic output was expressed as gross domestic product (GDP) and relevant data were obtained from the China Statistical Yearbook (NBSPRC, 2017b). We used constant prices for GDP (with a base year of 1997). In addition, owing to the lack of data, the provinces discussed in this paper do not include Tibet, Hong Kong, Macao, and Taiwan.

4. Results and discussion

4.1. Electricity generation intensity in different power sectors

Over the last two decades, the electricity generation intensity of China's power sector has shown a significant downward trend. As shown in Fig. 1, the electricity generation intensity of China's entire power sector decreased by 20.78%—from 0.1486 KWh/CNY in 1997 to 0.1177 KWh/CNY in 2016. This decrease shows that, with the rapid growth of China's economy, the scale of electricity generation per unit of economic output has decreased drastically and that the economic efficiency of the power sector has improved considerably. Nevertheless, the trend of electricity generation intensity varies across power sectors. Electricity generation intensity in China's thermal power sector has shown a significant decline—from 0.1209 KWh/CNY in 1997 to 0.0851 KWh/CNY in 2016—whereas the electricity generation intensity of the sustainable power sector has increased slightly—from 0.0276 KWh/CNY in 1997 to 0.0326 KWh/CNY in 2016. This difference shows that although the economic efficiency of the thermal power sector has improved more significantly than that of the sustainable power sector in recent years, the former is still lower than the latter, and the thermal power generation per unit of economic output is still higher than the sustainable power generation per unit of economic output.

[Insert Fig. 1 here.]

The changes in electricity generation intensity across the power sector are highly consistent with those of the thermal power sector, but significantly different from those of the sustainable power sector. As almost 80% of China's electricity generation comes from the thermal power sector, the decline in electricity generation intensity of the thermal power sector is a direct cause of the decline in the electricity generation intensity of the entire power sector. The improvement in the economic efficiency of the thermal power sector has led to improvement in the economic efficiency of the entire power sector. This result has been corroborated by Chen et al. (2018b). Despite that China has not been able to completely change its coal-fired power generation led structure and will not be able to do so in the coming decades (Chen et al., 2018b), innovation in China's electricity generation technology will still push China's thermal electricity generation from low efficiency and high emission to high efficiency and low emission, such as by developing supercritical or ultra-supercritical coal, integrated gasification combined cycles, and advanced ultra-supercritical techniques (Chen et al., 2018b).

4.2. Driving forces of the changes in electrical generation intensity of different power sectors

The impacts of electricity generation structure, electricity generation-to-consumption ratio, and electricity consumption intensity on the electricity generation intensity of the thermal and sustainable power sectors are shown in Figs. 2–4. Figures 2a, 3a, and 4a represent the cumulative influence of the three effects, whereas Figs. 2b, 3b, and 4b represent the annual influence of the three effects, respectively. Given that the cumulative influence is the aggregate of the annual influence and that the characteristics of the three effects are also reflected in the annual influence, the following is a summary for intuitively analyzing the historical role and influence of the electricity generation structure, electricity generation-to-consumption ratio, and electricity consumption intensity between 1997 and 2016. The analysis will mainly focus on the cumulative influence of these three effects.

Electricity consumption intensity is the key factor driving the decline in the electricity generation intensity of China's entire power sector. Data show that from 1997 to 2016, the cumulative influence of electricity consumption intensity on the changes in the electricity generation intensity of China's entire power sector was negative (from -0.3503 KWh/CNY to -0.9289 KWh/CNY); the cumulative influence of the electricity generation structure was always zero, whereas the cumulative influence of the electricity generation-to-consumption ratio increased from 0.0169 KWh/CNY to 0.3487 KWh/CNY.

The cumulative influence of the electricity generation structure in the thermal power sector is characterized by negative expansion, positive fluctuation, positive–negative fluctuation, and negative expansion. Meanwhile, the cumulative influence of the electricity generation structure in the sustainable power sector exhibited positive expansion, negative fluctuation, negative–positive fluctuation, and positive expansion. The cumulative influences of the electricity generation structure on the changes in electricity generation intensity of the thermal and sustainable power sectors were always the same in magnitude and opposite in direction, leading the sum of the electricity generation structures of the thermal and sustainable power sectors to always be zero.

Together, the thermal and sustainable power sectors constitute the entire power sector. The higher the proportion of thermal electricity generation, the lower the proportion of sustainable electricity generation. Thus, the more positive (or negative) the cumulative influence of the electricity generation structure, which is measured by the proportion of thermal electricity generation, on the changes in electricity generation intensity, the greater the negative (or positive) cumulative influence of the electricity generation structure, which is measured by the proportion of sustainable electricity generation, on the changes in electricity generation intensity.

Considering the sustainable core position of the thermal power sector in electricity supply and industrialization, and the policy preference of developing a sustainable power sector, parallel promotion has always existed between the thermal and sustainable power sectors. For example, policymakers have integrated coal resources and pithead power plants and shut down several small thermal power plants, as well as encouraging hydro, nuclear, and wind power projects. In addition, owing to the gradual improvement in the economic efficiency of the thermal power sector, and because the economic efficiency of the sustainable power sector has been higher than that of the thermal power sector in recent years, the cumulative influence direction of the electricity generation structure is not unique. In the long run, the market competitiveness of the thermal power sector will be weaker than that of the sustainable power sector. Furthermore, compared with continual improvement in the economic efficiency of the thermal power sector, vigorous promotion of sustainable electricity generation may be more conducive to reducing not only the electricity generation intensity of the entire power sector but also the electricity generation that drives China's economic growth and the consumption of required natural resources and energy inputs.

[Insert Fig. 2a and 2b here.]

The cumulative influence of the electricity generation-to-consumption ratio in the thermal power sector has a negative–positive characteristic. By contrast, the cumulative influence of the electricity generation-to-consumption ratio in the sustainable power sector has nearly maintained a positive characteristic, first fluctuating at a low level and then expanding with a "double hump."

The cumulative influence of the electricity generation-to-consumption ratio in the sustainable power sector is nearly always opposite in direction to the changes in electricity generation intensity of the entire power sector, which shows that the increase in the electricity generation-to-consumption ratio in the sustainable power sector is conducive to decreasing the electricity generation intensity of the entire power sector, as the economic efficiency of the sustainable power sector is higher than that of the thermal power sector. The higher the electricity generation-to-consumption ratio of the sustainable power sector, the stronger the net electricity generation capacity of the sustainable power sector and the more likely it is to promote the economic efficiency and reduce the electricity generation intensity of the entire power sector.

However, although the cumulative influence of the electricity generation-to-consumption ratio in the thermal power sector was opposite that of the entire power sector after 2004, i.e., the increase in the electricity generation-to-consumption ratio of the thermal power sector also contributed to the decrease in the electricity generation intensity of the entire power sector, the cumulative influence of the electricity generation-to-consumption ratio of the thermal power sector was consistent with the direction of the changes in electricity generation intensity of the entire power sector before 2004. Thus, the electricity generation intensity of the entire power sector can be reduced solely by decreasing the electricity generation-to-consumption ratio of the thermal power sector.

In recent years, China’s thermal electricity generation technology has steadily improved and several small thermal power plants with lower economic efficiency have been integrated and shut down, thereby increasing the economic efficiency of the thermal power sector. Thus, the greater the net electricity generation capacity of the thermal power sector, the more conducive it will be to reducing the electricity generation intensity of the entire power sector. Because China’s thermal electricity generation technology was relatively lagging several years ago, the many low economic efficiency thermal power plants had restricted economic efficiency improvements for the entire thermal power sector. Local governments used to encourage and accept extensive economic development because of the abundant sources of taxation from those low economic efficiency thermal power plants. Thus, it is possible to promote the electricity generation intensity of the entire power sector solely by reducing the net electricity generation capacity of the thermal power sector. Note that the cumulative influence of the electricity generation-to-consumption ratio in the sustainable power sector is greater than that in the thermal power sector. Thus, in the long run, prioritizing incentives to increase the net electricity generation capacity of the sustainable power sector may make it easier to reduce the electricity generation intensity in the entire power sector.

[Insert Fig. 3a and 3b here.]

With 2004 and 2007 as turning points, the cumulative influence of the electricity consumption intensity in the thermal power sector shows a high “three-step” negative fluctuation. Similarly, the cumulative influence of the electricity consumption intensity in the sustainable power sector shows a low “three-step” negative fluctuation.

On the one hand, the cumulative influences of electricity consumption intensity in the thermal and sustainable power sectors were nearly the same in direction as the changes in electricity generation intensity across the entire power sector, showing that in both sectors, the decline in electricity generation intensity contributes to the decline in the electricity generation intensity of the entire power sector. Reducing the electricity consumption per unit of economic output decreases the demand for electricity, thereby indirectly reducing the scale of electricity generation required. The positive situation is mainly caused by the dramatic improvement in industrial electricity consumption efficiency. Recent encouragement of innovation and entrepreneurship has led to continued breakthroughs in industrial energy saving technology, especially in electricity technology. For example, industries have reduced their electricity consumption by promoting energy-saving supply electricity systems, applying energy-saving lights and high-efficiency electric machinery, and optimizing electricity consumption management.

On the other hand, the cumulative influence of the electricity consumption intensity of the thermal power sector is significantly greater than that of the sustainable power sector. Thus, compared with the sustainable power sector, reducing the electricity consumption intensity of the thermal power sector is more conducive to reducing the electricity consumption intensity of the entire power sector. The scale of sustainable electricity consumption is significantly lower than the scale of thermal electricity consumption and most extensive electricity consumption industries and plants often consider improvements in economic efficiency of consuming thermal electricity. In addition, the Chinese government has advocated for the transformation from thermal power to clean and renewable power in recent years. The decline in electricity consumption intensity has mainly occurred in the thermal power sector. Hence, in the long run, continuing to encourage a reduction in electricity consumption intensity in the thermal power sector may make it easier to reduce the electricity generation intensity of the entire power sector.

[Insert Fig. 4a and 4b here.]

Based on our newly developed factorial nested RLI decomposition technique, Figs. 5–7 report the influences of the production electricity consumption, residential electricity consumption, and electricity consumption loss intensities. Figures 5a, 6a, and 7a report the cumulative influences of the three nested effects, whereas Figs. 5b, 6b, and 7b report the annual influences of the three nested effects. In the following, we focus on the cumulative influences of the three nested effects.

With 2004 and 2007 as the turning points, the cumulative influence of the production electricity consumption intensity in the thermal power sector shows a high level of "three-step" negative fluctuation. Similarly, the cumulative influence of the production electricity consumption intensity in the sustainable power sector presents a low level of "three-step" negative fluctuation.

The cumulative influences of production electricity consumption intensity in both the thermal and sustainable power sectors are consistent with the cumulative influences of the electricity consumption intensity of the two sectors because both thermal and sustainable electricity consumption in the production sector occupy the highest proportion of electricity consumption. Meanwhile, the cumulative influence of the electricity consumption intensity of the thermal and sustainable power sectors is the continuation of the cumulative influence of the production electricity consumption intensity in the two sectors. Thus, in the long run, the Chinese government should first encourage the reduction in production electricity consumption intensity of the thermal power sector.

[Insert Fig. 5a and 5b here.]

The cumulative influence of the residential electricity consumption intensity of the thermal power sector is characterized by a change from positive to negative fluctuation, taking 2003 as the turning point. By contrast, the cumulative influence of the residential electricity consumption intensity of the sustainable power sector shows a positive fluctuation.

The cumulative influence of residential electricity consumption intensity on the sustainable power sector is quite different from that of electricity consumption intensity. The higher the residential electricity consumption intensity of the sustainable power sector, the easier it is to reduce the electricity generation intensity of the entire power sector because the combination of the lower proportion of sustainable electricity and the lower proportion of electricity consumption in the residential sector makes it possible to moderately expand sustainable electricity consumption in peoples' daily lives to achieve economies of scale, reduce the marginal cost of electricity consumption, and improve the efficiency of electricity consumption. As yet, the average electricity consumption in residential sector has been lower than that in other countries. Due to the promotion of home appliances in the countryside, the promotion of electrical energy-saving marks, and the implementation of stepped electricity price, the efficiency of electricity consumption has been increasing.

There is a large difference between the cumulative influences of residential electricity consumption intensity and those of electricity consumption intensity in the thermal power sector before 2003. The higher the residential electricity consumption intensity in the thermal power sector, the easier it was to reduce the electricity generation intensity of the entire power sector because the lower proportion of thermal electricity in the residential sector can reduce the marginal cost of electricity consumption and improve the efficiency of electricity consumption by expanding the consumption of thermal electricity in peoples' daily lives. Once the thermal electricity consumption exceeds the threshold, expanding thermal electricity consumption is no longer beneficial in reducing the electricity generation intensity of the entire power sector. Hence, the Chinese government should encourage the reduction of residential electricity consumption intensity in the thermal power sector.

[Insert Fig. 6a and 6b here.]

The cumulative influence of electricity consumption loss intensity in the thermal power sector shows considerable negative expansion; in the sustainable power sector, electricity consumption loss intensity is generally characterized by minor negative expansion.

The direction of the cumulative influences of the electricity consumption loss intensity of the two power sectors is consistent with the direction of the cumulative influence of electricity generation intensity of the sectors. This result shows that reducing electricity consumption losses will help to decrease the electricity generation intensity of the entire power sector, as a reduction in electricity consumption losses can be regarded as an increase in electricity consumption efficiency. Likewise, the greater the electricity consumption, the higher the electricity consumption losses, and the easier it is to improve electricity consumption efficiency using the same advances in technology. Thus, in the long run, the Chinese government should focus on solving the problem of electricity loss in processes from generation to consumption.

[Insert Fig. 7a and 7b here.]

4.3. Driving forces of the differences in electricity generation intensity changes of different power sectors

Using our newly developed intertemporal nested decomposition RLI technique, Fig. 8 demonstrates the influences of the electricity generation structure, electricity generation-to-consumption ratio, production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity on the differences between the electricity generation intensity changes of the thermal and sustainable power sectors. Figures 8a and 8b report the cumulative and annual influences of the five effects, respectively. Next, we elaborate on the cumulative influences of these five effects.

The differences in the electricity generation intensity changes of the thermal and sustainable power sectors have been widening. Data show that the differences between the two power sectors widened from -0.3249 KWh/CNY to -1.2641 KWh/CNY between 1997 and 2016 (except for a slight decrease between 2002 and 2007), which implies that over the last two decades, the differences in the changes in electricity generation intensity of these two power sectors are becoming more obvious.

The influences of production electricity consumption intensity and electricity generation structure are larger than those of the electricity generation-to-consumption ratio, residential electricity consumption intensity, and electricity consumption loss intensity. From 1997 to 2016, the average cumulative influences of the electricity generation-to-consumption ratio, residential electricity consumption intensity, and electricity consumption loss intensity were only -0.0473 KWh/CNY, -0.0255 Kwh/CNY, and -0.0564 Kwh/CNY. In the same period, the average cumulative influences of the production electricity consumption intensity and electricity generation structure were -0.3979 KWh/CNY and -0.0630 KWh/CNY.

The change trend in the electricity generation structure most closely reflects the differences between the electricity generation intensity changes of the thermal and sustainable power sectors, because the cumulative influences of the electricity generation structure of the two power sectors are always the same in magnitude and opposite in direction. On the other hand, the influence of production electricity consumption intensity on the differences in the electricity generation intensity changes of the thermal and sustainable power sectors exceed the influence of the electricity generation structure, meaning that, in the long run, the key point to narrowing the differences in the electricity generation intensity changes of the two sectors is to improve the efficiency of their production electricity consumption.

[Insert Fig. 8a and 8b here.]

Figures 9–13 divide the intertemporal net influences of the five effects into the reporting period and base period impacts: the a and b subfigures illustrate the cumulative and annual influences of the five effects of the reporting and base periods, respectively. Next, we continue to elaborate on the cumulative influences of the five effects of the reporting and base periods. If one effect of the reporting period is that the differences in the electricity generation intensity changes deviate from the base period trend, then this effect is more likely to widen the differences between the electricity generation intensity changes of the thermal and sustainable power sectors. Furthermore, this effect is not conducive to the decline in the electricity generation intensity of the entire power sector and may affect the market competitiveness of different power sectors.

[Insert from Fig. 9a and 9b to Fig. 13a and 13b here.]

The trends in production electricity consumption intensity on the differences between the electricity generation intensity changes of the thermal and sustainable power sectors in the reporting period are mostly inconsistent with those in the base period, meaning that production electricity consumption intensity is the most important factor widening the differences between electricity generation intensity changes in the two power sectors. The market competitiveness between the thermal and sustainable power sectors can be adjusted only by narrowing the cumulative influence of the production electricity consumption intensity between the reporting and base periods on the differences in the electricity generation intensity changes of the two power sectors.

5. Conclusions and policy implications

In this paper, we have analyzed the determinants of the changes in electricity generation intensity in China and uncovered the reasons for the differences in the changes in electricity generation intensity between the two power sectors. We have developed a new factorial–intertemporal nested decomposition technique using the RLI and consider electricity generation and consumption together. This paper attributes the changes in electricity generation intensity and the differences in the changes in electricity generation intensity of the thermal and sustainable power sectors to their electricity generation structure, electricity generation-to-consumption ratio, production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity. The main findings of our study are as follows:

Although the electricity generation intensity of the sustainable power sector has always been lower than that of the thermal power sector, the latter has declined considerably in the recent years; nevertheless, it remains the key sector in determining the changes in the electricity generation intensity of the entire power sector. Electricity consumption intensity is the key effect driving the reduction in the electricity generation intensity of the entire power sector.

Comparing the thermal and sustainable power sectors, the cumulative influences of the electricity generation structure of the two sectors are the same in magnitude but opposite in direction. In contrast, the cumulative influence of the electricity generation-to-consumption ratio in the sustainable power sector is greater than that in the thermal power sector—the former nearly maintains a positive impact, whereas the latter has experienced a negative-to-positive impact. In addition, the cumulative influence of the electricity consumption intensity in the thermal sector shows a high level of three-step negative fluctuation, whereas the cumulative influence of this effect on the sustainable power sector shows a low level of three-step negative fluctuation.

After decomposing the electricity consumption intensity of the two power sectors into the production electricity consumption intensity, residential electricity consumption intensity, and electricity consumption loss intensity, we found that the cumulative influence of production electricity consumption intensity on the electricity generation intensity of the entire power sector exceeds the cumulative influence of the ECI effect of residential electricity consumption intensity and electricity consumption loss intensity; moreover, the influence of the former is similar to that of the overall electricity consumption intensity. Further, we found that the differences in the changes in electricity generation intensity of the thermal and sustainable power sectors have been widening over the last two decades, mainly because of the influence of production electricity consumption intensity. Furthermore, the trends of production electricity consumption intensity on the differences in the changes in the electricity generation intensity of the thermal and sustainable power sectors during the reporting period were inconsistent with those in the base period.

The policy implications of our findings are as follows:

First, the Chinese government should continue to promote the efficiency of electricity generation and reduce the scale of electricity generation per unit of economic output. Specifically, policymakers should encourage research and development and promote the transformation of low-efficiency and high-emission electricity generation modes beneficial to the thermal power sector to high-efficiency and low-emission power generation modes.

Second, despite significant improvements in the economic efficiency of the thermal power sector in recent years, the scale of electricity required per unit of economic output in the sustainable power sector has been significantly lower than in the thermal power sector. Therefore, compared with continual improvement in the economic efficiency of the thermal power sector, vigorous promotion of sustainable electricity generation may be more conducive to reducing not only the electricity generation intensity of the entire power sector, but also the electricity generation that drives China's economic growth and the consumption of the required natural resources and energy inputs.

Third, considering that the increase in the electricity generation-to-consumption ratio in the sustainable power sector is more conducive to reducing the electricity generation intensity of the entire power sector, the Chinese government can moderately increase the net capacity of sustainable electricity by controlling and digesting the net capacity of thermal electricity so as to drive the economic efficiency of the entire power sector.

Fourth, because the overall decline in electricity generation intensity over the last two decades has mainly resulted from the decline in the electricity consumption intensity of the thermal power sector, especially in the production electricity consumption intensity, the Chinese government can not only directly reduce the production electricity consumption intensity of the thermal power sector, but also improve the efficiency of thermal electricity consumption—especially the utilization rate of production thermal electricity consumption—to indirectly reduce the electricity generation intensity of the entire power sector.

Finally, considering that the electricity consumption loss intensity is also an important factor affecting the electricity generation intensity of the entire power sector, the Chinese government should also strengthen the construction of power transmission infrastructure to minimize electricity loss during transmission.

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Appendix A

The formulas for deducing the differences between the changes in the electricity generation intensity of the thermal and sustainable power sectors are as follows:

$$\begin{aligned}\Delta^{thermal-sust}EGI_{egs}^{t} &= \left(EGS^{thermalt}-EGS^{sustt}\right)\cdot EGC^{b}\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot EGC^{b}\cdot\left(ECI^{t}-ECI^{b}\right)\\ &+\frac{1}{3}\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\cdot\left(ECI^{t}-ECI^{b}\right)\end{aligned} \tag{A.1}$$

$$\begin{aligned}\Delta^{thermal-sust}EGI_{egs}^{b} &= \left(EGS^{thermalb}-EGS^{sustb}\right)\cdot EGC^{b}\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot EGC^{b}\cdot\left(ECI^{t}-ECI^{b}\right)\\ &+\frac{1}{3}\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\cdot\left(ECI^{t}-ECI^{b}\right)\end{aligned} \tag{A.2}$$

$$\begin{aligned}\Delta^{thermal-sust}EGI_{egc}^{t} &= \left(EGC^{t}-EGC^{b}\right)\cdot EGS^{thermalb}\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGC^{t}-EGC^{b}\right)\cdot\left(EGS^{thermalt}-EGS^{sust}\right)\cdot ECI^{b}\\ &+\frac{1}{2}\left(EGC^{t}-EGC^{b}\right)\cdot EGS^{thermalb}\cdot\left(ECI^{t}-ECI^{b}\right)\\ &+\frac{1}{3}\left(EGC^{t}-EGC^{b}\right)\cdot\left(EGS^{thermalt}-EGS^{sust}\right)\cdot\left(ECI^{t}-ECI^{b}\right)\end{aligned} \tag{A.3}$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{egc}^{b} =& \left(EGC^{t}-EGC^{b}\right)\cdot EGS^{sustb}\cdot ECI^{b} \\ &+\frac{1}{2}\left(EGC^{t}-EGC^{b}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot ECI^{b} \\ &+\frac{1}{2}\left(EGC^{t}-EGC^{b}\right)\cdot EGS^{sustb}\cdot\left(ECI^{t}-ECI^{b}\right) \\ &+\frac{1}{3}\left(EGC^{t}-EGC^{b}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot\left(ECI^{t}-ECI^{b}\right)\end{aligned} \quad (A.4)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecip}^{t} =& \left(ECI^{prodt}-ECI^{prodb}\right)\cdot EGS^{thermalb}\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot EGS^{thermalb}\cdot\left(EGC^{t}-EGC^{b}\right) \\ &+\frac{1}{3}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot\left(EGS^{thermalb}-EGS^{sustt}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\end{aligned} \quad (A.5)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecip}^{b} =& \left(ECI^{prodt}-ECI^{prodb}\right)\cdot EGS^{sustb}\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot EGS^{sustb}\cdot\left(EGC^{t}-EGC^{b}\right) \\ &+\frac{1}{3}\left(ECI^{prodt}-ECI^{prodb}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\end{aligned} \quad (A.6)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecir}^{t} =& \left(ECI^{resit}-ECI^{resib}\right)\cdot EGS^{thermalb}\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{resit}-ECI^{resib}\right)\cdot\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{resit}-ECI^{resib}\right)\cdot EGS^{thermalb}\cdot\left(EGC^{t}-EGC^{b}\right) \\ &+\frac{1}{3}\left(ECI^{resit}-ECI^{resib}\right)\cdot\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\end{aligned} \quad (A.7)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecir}^{b} =& \left(ECI^{resit}-ECI^{resib}\right)\cdot EGS^{sustb}\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{resit}-ECI^{resib}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{resit}-ECI^{resib}\right)\cdot EGS^{sustb}\cdot\left(EGC^{t}-EGC^{b}\right) \\ &+\frac{1}{3}\left(ECI^{resit}-ECI^{resib}\right)\cdot\left(EGS^{thermalb}-EGS^{sustb}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\end{aligned} \quad (A.8)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecil}^{t} =& \left(ECI^{losst}-ECI^{lossb}\right)\cdot EGS^{thermalb}\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{losst}-ECI^{lossb}\right)\cdot\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot EGC^{b} \\ &+\frac{1}{2}\left(ECI^{losst}-ECI^{lossb}\right)\cdot EGS^{thermalb}\cdot\left(EGC^{t}-EGC^{b}\right) \\ &+\frac{1}{3}\left(ECI^{losst}-ECI^{lossb}\right)\cdot\left(EGS^{thermalt}-EGS^{sustt}\right)\cdot\left(EGC^{t}-EGC^{b}\right)\end{aligned} \quad (A.9)$$

$$\begin{aligned}\Delta^{thermal-sust} EGI_{ecil}^{b} = & \left(ECI^{losst} - ECI^{lossb}\right) \cdot EGS^{sustb} \cdot EGC^{b} \\ & + \frac{1}{2}\left(ECI^{losst} - ECI^{lossb}\right) \cdot \left(EGS^{thermalb} - EGS^{sustb}\right) \cdot EGC^{b} \\ & + \frac{1}{2}\left(ECI^{losst} - ECI^{lossb}\right) \cdot EGS^{sustb} \cdot \left(EGC^{t} - EGC^{b}\right) \\ & + \frac{1}{3}\left(ECI^{losst} - ECI^{lossb}\right) \cdot \left(EGS^{thermalb} - EGS^{sustb}\right) \cdot \left(EGC^{t} - EGC^{b}\right)\end{aligned} \tag{A.10}$$