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Decoupling and attribution analysis of industrial carbon emissions in Taiwan

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ABSTRACT

A deeper understanding of the decoupling status between carbon emissions and industrial growth as well as its influencing factors is very important in implementing targeted polices. This study applies decoupling analysis, index decomposition analysis, and attribution analysis to achieve three goals. First, the study explores the decoupling relationship between industrial growth and carbon emissions in Taiwan. Second, the factors influencing changes in industrial carbon intensity are explored. Finally, the contributions of industrial sub-sectors to each factor are analyzed. The results indicate that Taiwan's industrial growth and carbon emissions experienced a negative decoupling from 2007 to 2009 and a decoupling from 2009 to 2013. Energy intensity effect plays the dominant role in promoting decoupling, and both energy structure effect and industrial structure effect negatively impact decoupling. The *chemical materials*, *electrical and electronic machinery* and *basic metal industries* sub-sectors are primarily responsible for the energy intensity effect. Energy-intensive industries are the main contributors to the increase in energy structure and industrial structure effects. The study suggests that the Taiwanese government should establish targeted carbon reduction measures at sub-sector level. Adjusting the energy structure and industrial structure is also urgently required to promote the decoupling of carbon emissions from industrial growth.

1. Introduction

Energy saving and emissions reduction are of key interest to the international community. Taiwan's total carbon emissions ranked 23rd globally, accounting for 0.86% of total global emissions in 2011 [1]. Echoing the global vision of reducing carbon emissions, Taiwan has hosted four National Energy Conferences. At the first conference in 1998, strategies focused on upgrading energy efficiency were proposed. The government anticipated reducing greenhouse gas emissions by adjusting both energy structure and industrial structure. Prior to the 2015 United Nations Climate Change Conference, Taiwan proposed voluntary mitigation action to reduce carbon emissions by 20% by 2030 based on the 2005 levels, and to reduce carbon emissions down to 2005 levels by 2020 [2].

Industrial sectors play an important role in Taiwan's economic development; however, its high dependence on energy-intensive industries has resulted in the "coupling" (or co-dependence) of industrial growth and carbon emissions. According to the statistics provided by Directorate-General of Budget, Accounting and Statistics, Executive Yuan [3] and Bureau of Energy, Ministry of Economic Affairs [4,5], in 2013, Taiwan's industrial output accounted for 33.46% of its gross domestic product (GDP); the industrial energy consumption accounted for 38.27% of total energy consumption; and the industrial carbon emissions accounted for 48.98% of total emissions. In particular, energy-intensive industries, such as the *chemical materials*, *electrical and electronic machinery*, and *basic metal industries*, accounted for approximately 30% of Taiwan's total energy consumption and approximately 80% of the total industrial energy consumption.

Taiwan's goal is to achieve industrial growth without significantly increasing carbon emissions. In other words, it wants to decouple the relationship between carbon emissions and industrial growth. To support this goal, this paper first analyzes the decoupling relationship between Taiwan's industrial growth and carbon emissions, and discusses the factors influencing the decoupling status. It then further analyzes the contributions of different

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industrial sub-sectors to these factors. This research can assist the Taiwanese government in decoupling carbon emissions from industrial development, and achieving carbon emission reduction goals.

2. Literature review

Zhang [6] first applied the concept of decoupling in environmental studies. The Organization for Economic Co-operation and Development [7] developed decoupling as an indicator to describe the relationship between environmental pressure and economic performance and divided it into relative decoupling and absolute decoupling. To investigate the degree of decoupling, Vehmas et al. [8] subdivided decoupling into six possibilities: strong de-linking, weak de-linking, strong re-linking, weak re-linking, expansive re-linking and recessive de-linking. Juknys et al. [9] discussed the decoupling of Lithuania's natural resources consumption from its economic growth, using the concepts of primary decoupling, secondary decoupling, and double decoupling. Based on the research of Vehmas et al. [8], Tapio [10] introduced the elasticity theory into the decoupling indicator, and subdivided economy-environment decoupling into strong decoupling, weak decoupling, recessive decoupling, strong negative decoupling, expansive negative decoupling, recessive coupling, and expansive coupling.

In recent years, decoupling analysis has been widely used in studying the relationship between environmental and economic variables. Climent and Pardo [11] considered several decoupling factors and investigated the relationship between energy consumption and GDP in Spain from 1984 to 2003. Caneghem et al. [12] analyzed the decoupling of environmental effects and economic growth in the Flemish industrial sector from 1995 to 2006. Zhang and Wang [13] measured the decoupling of economic growth and carbon emissions in Jiangsu province, China, from 1995 to 2009.

In addition to using decoupling indices to analyze economy-environment relationships, structural decomposition analysis (SDA) and index decomposition analysis (IDA) have also been applied to analyze the driving factors leading to environmental changes [14–16]. The SDA method uses an input-output model. Rose and Casle [17] presented the theoretical foundation and main characteristics of this method, positing that conclusions drawn using SDA were more accurate than those using IDA. The disadvantage of SDA is its high data requirements, restricting its application. The IDA method adopts an index concept, and decomposes the research object, such as energy consumption or carbon emissions, into several relevant factors. There are several types of IDA methods, including the Lasperes Index, arithmetic mean Divisia Index, logarithmic mean Divisia Index (LMDI), Paashe Index and Fisher Ideal Index. Among these, the LMDI method has been widely used in decomposition analysis; its advantages include having an independent pathway, zero residuals, and consistent aggregation [18–20].

An increasing number of studies have used the LMDI approach to decompose carbon emission changes. Liu et al. [21] analyzed the changes in industrial carbon emissions from 36 industrial sectors in China between 1998 and 2005, and found that industrial activity and energy intensity were the main causes of industrial carbon emission changes. Using China power industry data from 1991 to 2009, Zhang et al. [22] found that the economic activity effect was the most important contributor to increased carbon emissions from electricity consumption. Further, they found that the efficiency of electricity generation played a dominant role in the reduction of carbon emissions in the power industry.

Other researchers have applied the LMDI method to study the decomposition of carbon intensity changes. Chen [23] and Liu et al. [24] decomposed the carbon intensity of 38 industrial sectors in China between 1980-2008 and 1996–2008, respectively. Both studies concluded that the energy intensity factor was mainly responsible for reducing carbon intensity. Li et al. [25] compared the different factors influencing the carbon intensity of eastern and central China under two different forms of carbon intensity (i.e., carbon emissions per capita and carbon emissions per unit GDP). They found that the income effects were the primary driving force causing the variations in CO_2 emissions per capita between eastern and central China, and energy efficiency effects remained the main factor resulting in downward trend of CO_2 emissions per unit of GDP by region.

The researchers above either decoupled economic growth and carbon emissions, or decomposed the factors influencing carbon emissions from one single dimension. De Freitas and Kaneko [26] noted that it was more effective to combine the decoupling index and the factor decomposition method. This facilitated measuring the relationship between economic growth and carbon emissions, and analyzing the factors influencing carbon emissions simultaneously. Using a simple average Divisia index method, Lu et al. [27] decomposed the carbon emissions of highway vehicles in Germany, Japan, South Korea, and Taiwan during 1990–2002 into five influencing factors. They then compared the decoupling relationship between economic growth, transport energy demand and CO_2 emissions. De Freitas and Kaneko [26] investigated the decoupling relationship between the growth rates in economic activity and CO_2 emissions in Brazil from 2004 to 2009 using the LMDI method. They pointed out that carbon intensity and energy mix were the determining factors in reducing carbon emissions. Similar studies were conducted by Ren and Hu [28], Ren et al. [29], and Zhang and Da [30].

In recent years, some researchers have used the attribution analysis method proposed by Choi and Ang [31] to measure each sub-sector's contribution to the decomposition factor effect. Liu et al. [24] conducted the LMDI decomposition and attribution analysis of the carbon intensity in China's industrial sector from 1996 to 2012. They found that the energy intensity effect was the dominant factor in reducing carbon intensity, and that the chemical, iron and steel, metal and machinery, and cement and ceramic sub-sectors were the most representative ones. Fernández González et al. [32] and Fernández González [33] conducted attribution analysis on the energy intensity effect and the sectoral structure effect on the European energy intensity changes, respectively. Fernández González et al. [34] extended Choi and Ang's approach [31] and analyzed the contributions of both regions and sectors to the percentage change in the emission coefficient effect. Su and Ang [35] introduced the attribution analysis of the generalized Fisher index to SDA studies. The attribution analysis has also been used to research energy consumption and carbon emission dynamics in Mexico and Korea [36,37].

The present work contributes to this research foundation in two aspects. First, this paper combines decoupling analysis, decomposition analysis, and attribution analysis to systematically investigate the relationship between industrial growth and carbon emissions in Taiwan. To the best of our knowledge, the current literature concentrates mainly on decoupling and its influencing factors. These studies do not conduct deep analysis to explore the contribution of individual sub-sectors. Further, the existing attribution analysis literature does not incorporate the decoupling analysis. Given this, this paper explores the decoupling relationship between industrial growth and carbon emissions and the factors influencing changes in industrial carbon intensity. Then, the contributions of industrial sub-sectors to each factor are quantified. This helps to identify the causes of the decoupling state