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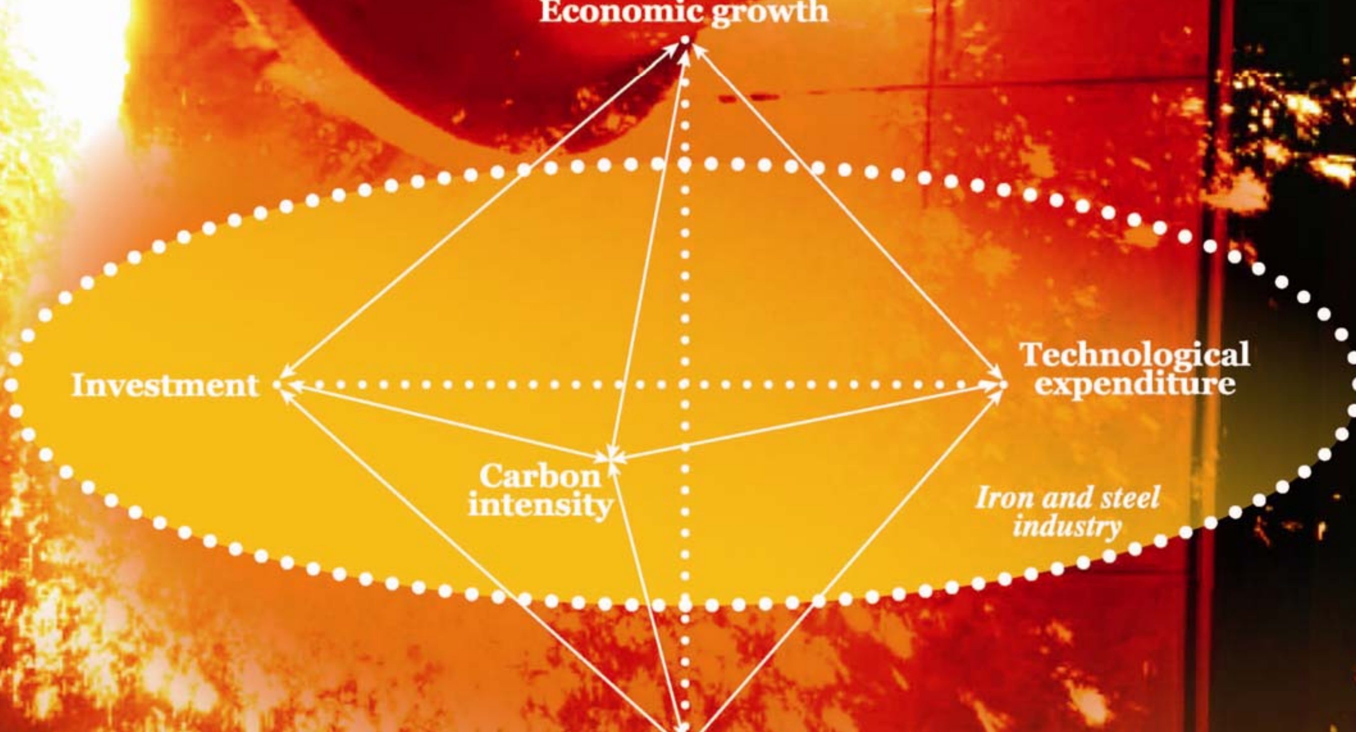

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Low-carbon transition of iron and steel industry in China: Carbon intensity, economic growth and policy intervention

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ABSTRACT

As the biggest iron and steel producer in the world and one of the highest CO_2 emission sectors, China's iron and steel industry is undergoing a low-carbon transition accompanied by remarkable technological progress and investment adjustment, in response to the macroeconomic climate and policy intervention. Many drivers of the CO_2 emissions of the iron and steel industry have been explored, but the relationships between CO_2 abatement, investment and technological expenditure, and their connections with the economic growth and governmental policies in China, have not been conjointly and empirically examined. We proposed a concise conceptual model and an econometric model to investigate this crucial question. The results of regression, Granger causality test and impulse response analysis indicated that technological expenditure can significantly reduce CO_2 emissions, and that investment expansion showed a negative impact on CO_2 emission reduction. It was also argued with empirical evidence that a good economic situation favored CO_2 abatement in China's iron and steel industry, while achieving CO_2 emission reduction in this industrial sector did not necessarily threaten economic growth. This shed light on the dispute over balancing emission cutting and economic growth. Regarding the policy aspects, the year 2000 was found to be an important turning point for policy evolution and the development of the iron and steel industry in China. The subsequent command and control policies had a significant, positive effect on CO_2 abatement.

Introduction

The iron and steel industry has been at the center of the economic and environmental transformations in China, from the movement of backyard steel production during the Great Leap Forward in the 1950s (Cook and Murray, 2001) to its fast expansion since China's reform and opening up, from the sanction of Tieben Steel in 2003 (Mei and Pearson, 2011) to the ongoing stringent capacity control of the iron and steel industry to mitigate air pollution in East China (Stanway, 2014). On one hand, the iron and steel industry is vital to the country's economic power. It produced 658.0 million tons of pig iron and 716.5 million tons of crude steel in 2012, representing 59.1% and 46.4% of the world production, respectively (WSA, 2013) (Fig. 1). On the other hand, the low-carbon transition of the industry, which accounts for 10% of total domestic CO_2 emissions and ranks as the third largest industrial CO_2 emitter (Zeng et al., 2009; Zhang et al., 2012), is crucial for meeting the country's CO_2 targets.

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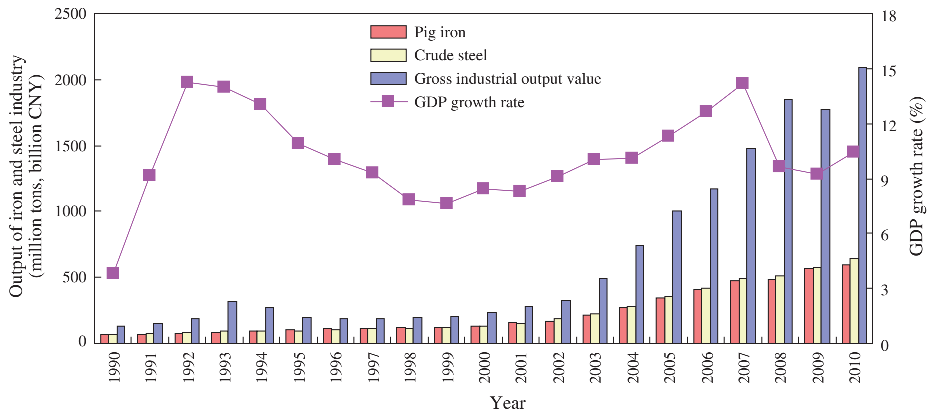

Fig. 1 – Output of iron and steel industry and economic growth in China from 1990 to 2010 (CISA, 1991–2011; EBCSY, 1991–2011; NBSC, 2013).

China's iron and steel industry is undergoing a low-carbon transition accompanied by remarkable technological progress and investment adjustment, in response to the macroeconomic climate and policy intervention (Fujii et al., 2010; Hu et al., 2009; Kim and Worrell, 2002; Milford et al., 2013). This economic–environment interconnection shapes the profound transformation of the iron and steel industry. A variety of studies have addressed the drivers of CO_2 emissions in the iron and steel industry, as shown in Table 1, but the relationships between CO_2 abatement, investment and technological expenditure, and their connections with the economic growth and policy intervention in China, have not been conjointly and empirically examined. The most prominent part of the existing studies adopted index decomposition analysis (IDA) to explore the direct factors influencing the CO_2 emissions of the industry, including activity level, product structure, energy efficiency, fuel share, energy consumption and emission factor. They clearly calculated the contribution from each of these straight-forward factors, but they were weak in analyzing the underlying macroeconomic factors and policy influence. There were also a couple of studies that were able to accommodate a number of miscellaneous drivers with larger-size bottom-up models or integrated bottom-up/top-down models. They were good at analyzing the technology aspect from the bottom level and their possible influence on future CO_2 emissions with usually exogenous scenario settings on economic and policy dimensions. However, only limited implications can be drawn on the crucial bidirectional interactions between CO_2 emissions and the economic aspects. A few other studies also emphasized or briefly mentioned the importance of taking into account these interactions, especially for China (Milford et al., 2013), but did not provide answers.

To fill the knowledge gap, our study targets the key questions concerning the relationships between CO_2 abatement, investment and technological expenditure of the iron and steel industry, and

Table 1 – Literature survey on drivers of CO_2 emissions of the iron and steel industry.

Method	Driver	Country or region	Literature
Index decomposition analysis (IDA)	Activity level	Brazil, China, India, Mexico, South Korea, USA	Kim and Worrell (2002), Sheinbaum et al. (2010), Ozawa et al. (2002), Sun et al. (2011), Sun et al. (2012)
	Product structure	Brazil, China, India, Mexico, South Korea, USA	Kim and Worrell (2002), Sheinbaum et al. (2010), Ozawa et al. (2002)
	Energy efficiency	Brazil, China, India, Mexico, South Korea, USA	Kim and Worrell (2002), Sheinbaum et al. (2010), Ozawa et al. (2002)
	Fuel share	Brazil, China, India, Mexico, South Korea, USA	Kim and Worrell (2002), Sheinbaum et al. (2010); Ozawa et al. (2002), Sun et al. (2011), Sun et al. (2012)
	Energy consumption	China	Sun et al. (2011), Sun et al. (2012)
	Emission factor	China	Sun et al. (2011), Sun et al. (2012)
Climate change policy models (bottom-up models, integrated bottom-up/top-down models)	Technological progress	Germany, China, Europe	Pardo and Moya (2013), Lutz et al. (2005), Wang et al. (2007); Schumacher and Sands (2007)
	Scale and direction of investment	Germany	Lutz et al. (2005)
	Carbon tax, carbon price	Germany, Japan	Gielen and Moriguchi (2002a), Lutz et al. (2005), Schumacher and Sands (2007)
	Trade barrier	Japan	Gielen and Moriguchi (2002b)
	Policy	China	Wang et al. (2007)
Dynamic programing model	Economic growth	India	Das and Kandpal (1998)
Material flow analysis	Scale and direction of investment	China, the world	Pauliuk et al. (2011), Milford et al. (2013)
Qualitative analysis	Policy	China	Rock et al. (2013), Lv and Yang (2011)

their connections with economic growth and policy intervention in China. In detail, we aim to answer the following three questions:

(1) What are the relationships among CO_2 emission reduction, investment, and technological expenditure in the iron and steel industry?
(2) How does economic growth influence CO_2 abatement, investment, and technological expenditure in the iron and steel industry? Conversely, how do CO_2 abatement, investment and technology expenditure in the iron and steel industry affect the national economy?
(3) How have the policies affected CO_2 emission reduction in China's iron and steel industry? Has the evolving policy intervention led to structural change in the low-carbon transition of China's iron and steel industry?

We provide an overview of the iron and steel industry in China in Section 1, and propose and illustrate a conceptual model and an econometric model in Section 2. Results are presented in Section 3, and discussed in Section 4. Finally, conclusions and policy implications are drawn in Section 5.

1. Overview of the development of the iron and steel industry in China

1.1. Carbon intensity

As shown in Fig. 2, CO_2 emission intensity presented a downward trend due to several reasons, such as technological progress. CO_2 emission intensity in physical terms (ton CO_2 per ton of crude steel, abbreviated as ton/tcs) first decreased from 5.79 ton/tcs in 1990 to 5.37 ton/tcs in 1992, then increased to 6.36 ton/tcs in 1995, and finally dropped to 2.76 ton/tcs in 2010 with an average annual reduction rate of 5.4% from 1995 to 2010. CO_2 emission intensity in monetary terms (ton CO_2 per unit of gross industrial output value, abbreviated as ton/10^3 CNY) first decreased from 2.98 ton/10^3 CNY in 1990 to 1.37 ton/10^3 CYN in 1993, then increased to 1.80 ton/10^3 CNY in 1997, and finally dropped to 0.34 ton/10^3 CNY in 2010 with an average annual reduction rate of 12.0% from 1997 to 2010.

1.2. Investment

A major driver of the development of the iron and steel industry is the overall increasing investment during the past 20 years. Using the price level of 1990 as a baseline, the annual investment in fixed assets reached a peak of 167.3 billion CNY in 2009, compared with 12.7 billion CNY in 1990 (Fig. 3). The huge investment led to a tremendous expansion in production capacity, indicated by the striking increase of industrial output in Fig. 1. On one hand, it satisfied the high demand for iron and steel products required by the soaring economic growth in China; on the other hand, the high asset value from accumulated investment raised the risk of oversupply (Milford et al., 2013).

1.3. Technological progress

Remarkable technological progress is another characteristic of the development in the iron and steel industry. As shown in Fig. 3, there was an exponential increase in the annual internal expenditure on science and technology activities, which drove the upgrading of the industry in technological terms. From 1990 to 2000, new plants mainly adopted mature and advanced techniques and equipment, such as continuous thin slab casting and rolling technology, and high power direct-current electric arc furnaces, narrowing the technology gap between domestic and foreign steel industries. Meanwhile, backward technologies and equipment were eliminated step by step in an orderly way according to plan, such as open hearth furnaces, open-train mills, and pack-rolled sheet. In the 21st century, technological expenditure was focused on achieving high-class product quality, adoption of energy-saving technologies, introduction of international advanced techniques and equipment, and realizing the localization of key production equipment (Fujii et al., 2010; Li and Wang,

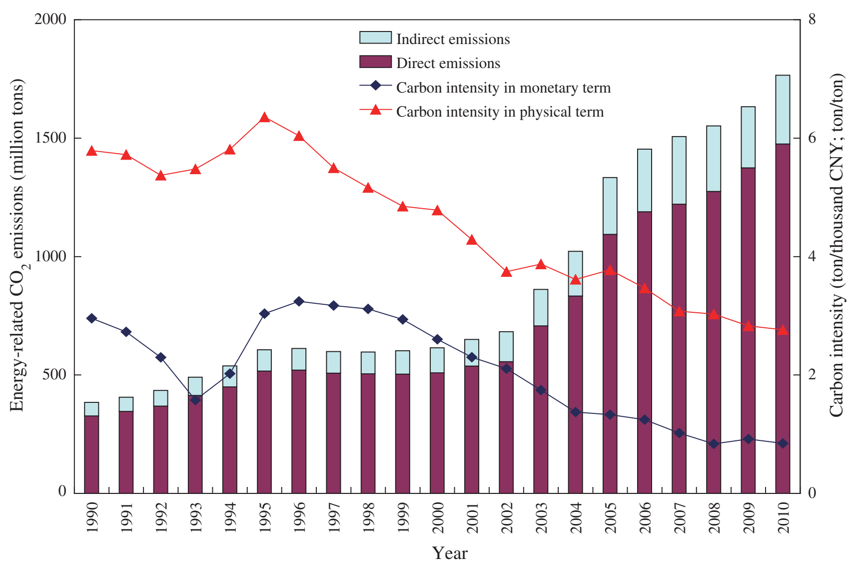

Fig. 2 – Energy-related CO_2 emissions and carbon intensity in China's iron and steel industry from 1990 to 2010.

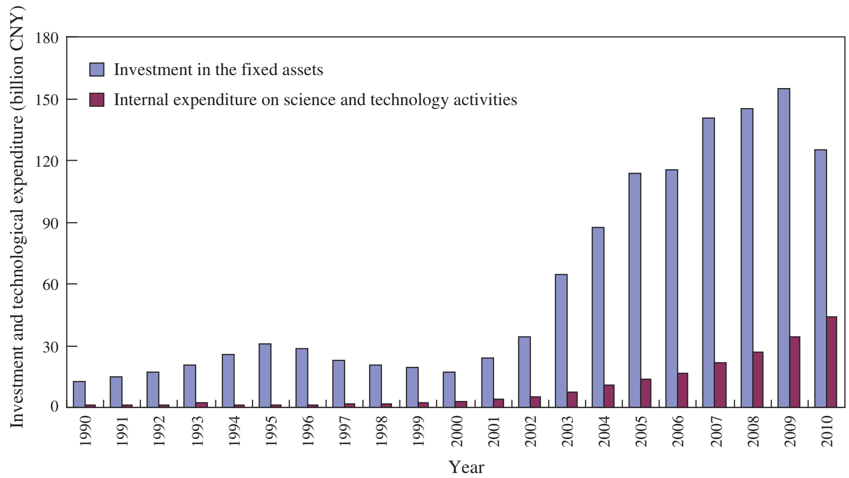

Fig. 3 – Investment in the fixed assets and expenditures on science & technology activities in China's iron and steel industry from 1990 to 2010 (NBSC, 1991–2011; EBCSY, 1991–2011; NBSC and MSTC, 1991–2011).

2009; Rock et al., 2013). These technological improvements have greatly improved productivity and efficiency in the industry.

1.4. *Economic growth*

As shown in Fig. 1, the GDP of China expanded from 1854.8 billion CNY in 1990 to 13,459.5 billion CNY in 2010, with an average annual GDP growth rate of 10.2% (1990 as price base year) (NBSC, 2013). The continuous market reforms released tremendous productivity. Investment, consumption and export presented strong impetus in driving economic growth. The economy of China is also undergoing a transition. It is aiming to eliminate the backward growth pattern featured by low efficiencies and high costs in terms of resources, energy and the environment, and to build a new growth paradigm, with efforts on promoting innovation, adjusting economic structure, and enhancing environment-friendliness.

1.5. *Policy intervention*

Since the development and upgrading transition of the iron and steel industry was high on the governmental agenda, it has always been a target sector for policy interventions. Generally speaking, the policies encouraged extensive growth without much consideration of the environmental costs in the 1990s. After the Asian financial crisis broke out in 1997, there was a large amount of surplus production capacity in China's steel industry, and most companies were in deficit. The government started to implement the working principle of "controlling total quantity, adjusting structure, and improving efficiency", and to promote the development strategy of "eliminating backward technologies, and speeding up industrial upgrading". They set the tone for the policy interventions since then. The State Council published a notice on controlling blind investment in iron and steel, electrolytic aluminum and cement industries in 2003. In 2005 the National Development and Reform Commission issued an exclusive policy document, "Development Policy of the Iron and Steel Industry", which aimed at technological upgrading, structural adjustment, competitiveness improvement, and pollution control for the industry. The policies afterwards further strengthened the environmental emphasis, and highlighted energy conservation and emission reduction, including differential power pricing, subsidies for energy-saving technological transformation, and preferential corporate income tax for comprehensive utilization of resources.

2. Methodology

2.1. *Conceptual model*

In order to answer the questions raised in Section 1, we proposed a corresponding conceptual model, as shown in Fig. 4. Five factors were included in the framework, *i.e.* the carbon intensity of the iron and steel industry, the investment in the iron and steel industry, the technological expenditure of the iron and steel industry, the economic growth, and the policies related to the iron and steel industry. The essence of the model is to extract and highlight these key aspects from a diverse array of factors and to conjointly examine the directions and magnitudes of their possible interconnections.

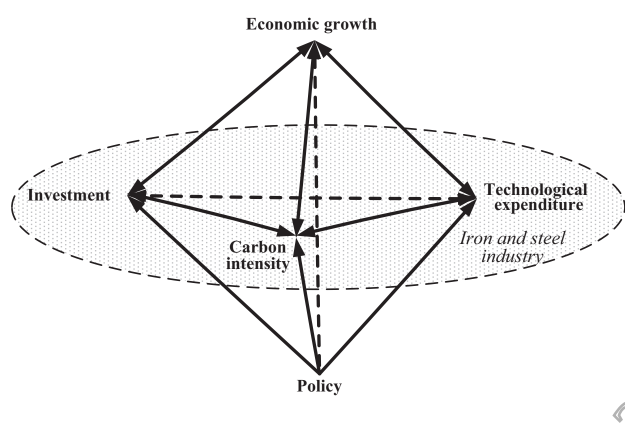

Fig. 4 – Conceptual framework.

Within the domain of the iron and steel industry, investment may have mixed effects on CO_2 emissions, mainly depending on the direction of investment. Investment in efficiency-improving or emission-cutting technologies and equipment as well as less-carbon-intensive but higher-value-added products can contribute to CO_2 abatement. In contrast, blind investment in capacity expansion can increase the risk of oversupply and price fall, worsening corporate revenues and operating conditions, which is unfavorable for the low-carbon transition. Many technologies that enterprises are willing to develop or adopt can provide solutions leading to higher productivity and carbon friendliness. Thus, intuitively, technological expenditure will contribute to CO_2 abatement. Nevertheless, the magnitude of the effect needs to be examined. There is more uncertainty when it comes to the effect from CO_2 abatement on investment and technological expenditure. It is the government's hope that CO_2 emission reduction can impose pressure on enterprises and industry, forcing the upgrading of technologies and the optimization of investment. However, this desired effect may be not significant, or in the worst scenario, one-sided stress on CO_2 emission reduction may become highly incompatible with profitability and undermine rational business calculations and the capacity for investment and technology innovation.

The relationship between the development of the iron and steel industry and economic growth has been studied (Das and Kandpal, 1998; Ghosh, 2006; Huh, 2011). However, the connections between economic growth and carbon intensity of the iron and steel industry are complicated. Economic growth causes increasing demand for iron and steel products. The magnitude of this effect is influenced by factors such as the economy's dependence on iron and steel. Whether responses to the increasing demand for iron and steel will drive up the carbon intensity or not is determined by the technology and investment decisions of the industry. If the demand was met by production expansion with laggard and high-emission technologies, the carbon intensity of the iron and steel industry would probably rise. If the demand was met with increasing productivity by spending on technologies, especially carbon-friendly technologies, the carbon intensity would drop or stay relatively stable. Policies can certainly play a role in regulating the technology and investment decisions of the industry. Likewise, the effect of CO_2 abatement of the iron and steel industry on economic growth is complicated by how the abatement is achieved. The transition of the iron and steel industry mirrors the transformations in the national economy. It is the government's hope that the CO_2 emission reduction can parallel the structural adjustment and technological upgrading of the industry, which will foster a more competitive iron and steel industry and provide sustaining impetus to economic growth. In light of the complexity, it is essential to empirically examine the bi-directional influences and carefully interpret the results and implications.

Policies are taken as an exogenous factor in the conceptual model. They can influence the other factors and provide external shocks to the system. Both of the two major types of policy instruments, *i.e.* command and control policies and market-based instruments, have played roles in regulating the iron and steel industry. Command and control policies mandate compliance with legislation. Market-based instruments provide incentives for corporate behavioral change. The effectiveness of these two types of policies needs to be examined. In addition, as reviewed in Section 1.5, the policies have been evolving, and during the evolution there may be turning points that mark structural change of the system.

2.2. Econometric model

The vector autoregression (VAR) model was used to explore the interrelationships among the factors that we identified in Fig. 4. A generic form of VAR model is illustrated below:

$$Y_t = \mu + A_1 Y_{t-1} + \ldots + A_p Y_{t-p} + \varepsilon_t; \quad t = p+1, p+2, \ldots, T \tag{1}$$

$$Y_{t-i} = \begin{pmatrix} Y_{1t-i} \\ Y_{2t-i} \\ \vdots \\ Y_{kt-i} \end{pmatrix}, i = 1, 2, \cdots, p; A_j = \begin{pmatrix} \alpha_{11.j} & \alpha_{12.j} & \cdots & \alpha_{1k.j} \\ \alpha_{21.j} & \alpha_{22.j} & \cdots & \alpha_{2k.j} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{k1.j} & \alpha_{k2.j} & \cdots & \alpha_{kk.j} \end{pmatrix}, \quad j = 1, 2, \cdots, p \tag{2}$$

$$\mu = (\mu_1, \cdots, \mu_k)'; \varepsilon_t = (\varepsilon_{1t}, \varepsilon_{2t}, \cdots, \varepsilon_{kt})' \tag{3}$$

where, Y_t is a vector of k endogenous variables; A_j is the coefficient matrix; μ is a vector of the constants; ε_t is a vector of non-autocorrelated disturbances; p is the lag order; the sample size is $T - p$.

VAR has become a widely used econometric model, especially in macroeconomics, since the 1980s. In model construction, it does not presume theoretical foundations that are usually difficult to prove satisfactorily. It has been used for analyzing and forecasting macroeconomic activities, testing Granger causality, and exploring the effects of policy and external stimuli through impulse response features (Greene, 2011). Greene (2011) summarized the merits of VAR models as follows: "researchers have found that simple, small-scale VARs without a possibly flawed theoretical foundation have proved as good as or better than large-scale structural equation systems".

In addition to economic research, there have been various studies applying VAR models, or closely related representations, such as the autoregressive distributed lag model (ARDL) and the vector error correction model (VECM), at the interface of environment, energy and the economy. Zhang and Cheng (2009) used a VAR model to analyze the relationships among carbon emissions, economic growth, energy use, capital, and urban population at the national level of China from 1960 to 2007. They testified that GDP Granger-caused energy consumption, and energy consumption Granger-caused CO_2 emissions, using Granger causality analysis. At the industry level, Zhao et al. (2013) applied the ARDL model, which is a single-equation model, to study the factors influencing the CO_2 emissions of China's power industry from 1980 to 2010. The CO_2 emissions were the dependent variable, and the added value of the sector, structure of the sector, and the technological progress were the independent variables. Granger causality tests and impulse response analyses were usually done in such studies to investigate relationships among variables and their dynamic features.

In our study, the VAR model is very suitable for examining the potential bi-directional relationships between CO_2 emissions, investment, and technology expenditure in the iron and steel industry, and their connections with the economic growth in China, as described in the conceptual model. Accordingly, we constructed a VAR equation system as follows:

$$Y_t = \mu + A_1 Y_{t-1} + \ldots + A_p Y_{t-p} + BX_t + \varepsilon_t \quad (4)$$

where, $Y_t = (CO2_t, GDP_t, Invest_t, Tech_t)'$ is a vector of endogenous variables; $X_t = (PolicyC_t, PolicyM_t)'$ is a vector of two exogenous, dummy variables; A_p and B are the corresponding coefficient matrices; μ is a vector of the constants; ε_t is a vector of non-autocorrelated disturbances; p is the lag order. A detailed description of the variables was listed in Table 2.

2.3. Data

Energy-related CO_2 emissions of the iron and steel industry were calculated according to the World Steel Association (WSA, 2009). Direct emission factors were calculated on the basis of the conversion factor from the International Energy Agency and World Steel Association, and low calorific values were derived from the China Energy Statistical Yearbook (NBSC, 1991–2011). Indirect emission factors from electricity were derived from coal consumption for power supply in the China Energy Statistical Yearbook (NBSC, 1991–2011). The calculation results of CO_2 emissions showed similar trends compared with the studies done by Price et al. (2002), Wang et al. (2007), and Zeng et al. (2009).

The data of the gross industrial output value of the iron and steel industry and the GDP growth rate were obtained from the China Statistical Yearbook (NBSC, 1991–2011). The data of investment in the fixed assets of the iron and steel industry were obtained from the China Steel Yearbook (EBCSY, 1991–2011) and China Statistical Yearbook (NBSC, 1991-2011). The data of internal expenditure on science and technology activities of the iron and steel industry were obtained from the China Statistical Yearbook on Science and Technology (NBSC and MSTC, 1991–2011) and China Statistical Yearbook (NBSC, 1991–2011). For data in monetary terms, the price inflation/deflation factor was eliminated by converting all values to the price level of 1990.

As for the value setting of the two dummy variables, we preselected two turning points, the years 2000 and 2006, in the policy evolution from 1990 to 2010, based on the characteristics of policies regarding the iron and steel industry. The year 2000 reflected the transition from encouraging policies that tolerated the extensive expansion of the industry to command and control policies that emphasized overall control, structural adjustment and efficiency improvement. The year 2006 marked the beginning of more stringent policies for the industry, and the emergence of market-based instruments functioning together with command and control instruments. Thus, the value of the two dummy variables were set as follows: PolicyC (Year $\geq$ 2000) = 1; PolicyC (1990 $\leq$ Year < 2000) = 0; PolicyM (Year $\geq$ 2006) = 1; PolicyM (1990 $\leq$ Year < 2006) = 0.

A logarithmic transformation was applied to the raw data. The data after the transformation were used in the model.

Table 2 – Description of variables.

Variables	Description	Indicators
CO2	Carbon intensity of iron and steel industry	Energy related CO_2 emissions divided by gross industrial output value of iron and steel industry
GDP	Economic growth	GDP growth rate
Invest	Investment of iron and steel industry	Investment in fixed assets
Tech	Technology expenditure of iron and steel industry	Internal expenditure on science and technology activities
PolicyC	Command and control policies	Dummy variable
PolicyM	Market-based policies	Dummy variable

3. Results

3.1. Stationarity of time series data

Stationarity tests were performed before the econometric estimation to avoid any spurious regression. The widely used KPSS test was adopted to examine the stationarity of the time series. The KPSS test of stationarity held a null hypothesis that the time series was stationary (Kwiatkowski et al., 1992). Table 3 presents the results of the test. The variables CO2, Invest, and Tech were non-stationary at the significance level of 5%, since their test statistic values were higher than 0.146. GDP was stationary at the significance level of 5%, since its test statistic value was lower than 0.146. The KPSS test was then applied to the first order differences of these variables. ΔCO2 and ΔTech were stationary at the significance level of 5%, and ΔGDP and ΔInvest were stationary at the significance level of 2.5%. Thus the first order differences of the variables were used in the VAR model.

Table 3 – Results of KPSS test.

Variables	Lag order	Test statistic	Variables	Lag order	Test statistic
CO2	0	0.401	ΔCO2	0	0.0908
	1	0.223		1	0.0714
	2	0.167		2	0.0783
GDP	0	0.101	ΔGDP	0	0.169
	1	0.0736		1	0.124
	2	0.069		2	0.117
Invest	0	0.312	ΔInvest	0	0 .161
	1	0.170		1	0.109
	2	0.127		2	0.0885
Tech	0	0 .430	ΔTech	0	0 .0685
	1	0.242		1	0.0714
	2	0.180		2	0.0754

Critical value of the test statistic for accepting the null hypothesis at different levels of significance: 0.119 (10%), 0.146 (5%), 0.176 (2.5%), 0.216 (1%).
Δ represents the first order difference.

3.2. Selection of lag order

Well-accepted criteria were used to examine the optimal lag order of the model. Given the length of the time series, variable numbers and the practical meanings, we set the second order as the maximum lag order. Longer lag length requires longer time series and greater sample size to make a valid estimation.

As shown in Table 4, the likelihood ratio (LR), Akaike's information criterion (AIC), and Hannan and Quinn information criterion (HQIC) supported the selection of the second order as the optimal order. The Schwarz's Bayesian information criterion (SBIC) supported a model without lagged variables, which did not conform to the basic idea of the model. So, we chose two as the lag order.

3.3. Regression results

The regression results are listed in Table 5. In Eq. (1), where ΔCO2 was the dependent variable, $\Delta CO2_{t-1}$, $\Delta CO2_{t-2}$, ΔGDP_{t-2}, $\Delta Tech_{t-1}$, $\Delta Tech_{t-2}$, and $PolicyC_t$ were significant at the 1% level; ΔGDP_{t-1} and $\Delta Invest_{t-2}$ were significant at the 5% level; and $\Delta Invest_{t-1}$ and $PolicyM_t$ were not statistically significant. In Eq. (2), where ΔGDP was the dependent variable, most variables were not significant except for $PolicyC_t$ and $PolicyM_t$; the R-sq value showed that the goodness-of-fit of this equation was less satisfactory than other equations. The situation was similar for Eq. (3), where ΔInvest was the dependent variable. Only $PolicyC_t$ and $PolicyM_t$ were significant at the 5% and 1% significance levels, respectively. In Eq. (4), where ΔTech was the dependent variable, $\Delta CO2_{t-2}$, $\Delta Tech_{t-2}$, and $PolicyC_t$ were significant at the 1% level; $\Delta CO2_{t-1}$ and ΔGDP_{t-2} were significant at the 5% level; and $\Delta Invest_{t-1}$, $\Delta Invest_{t-2}$, and $PolicyM_t$ were not significant.

Wald tests were performed to test the joint significance of coefficients. The results showed that coefficients in Eq. (1), Eq. (4) and the entire VAR model were jointly significant at the 1% level. All the eigenvalues were inside the unit circle, which indicated that the VAR model satisfied stability conditions. The results of Jarque–Bera tests, Skewness tests, and Kurtosis tests showed that the disturbances of Eqs. (1) and (4) were normally distributed. All the test results are shown in the Supporting materials.

3.4. Granger causality test

Granger causality was defined by Granger (1969) and Sims (1972) in the sense that time series variable x_t Granger-caused y_t if y_t can be better predicted by using the lagged values of both x_t and y_t than using the lagged values of y_t alone. The VAR can be used to test the Granger causality.

Granger causality results in Table 6 indicated that there was a bidirectional Granger causality relationship between ΔCO2 and ΔTech at the 1% significance level; ΔGDP and ΔInvest significantly Granger-caused ΔCO2 at the 1% and 10% significance levels, respectively; ΔGDP also significantly Granger-caused ΔTech at the 5% significance level. None of the variables had significant Granger causality effects on variables ΔGDP and ΔInvest.

Table 4 – Selection of lag order.

Lag order	Criterion			
	LR	AIC	HQIC	SBIC
0	–	−2.976	−2.894	−2.382[a]
1	40.303	−3.437	−3.246	−2.052
2	39.118[a]	−3.833[a]	−3.533[a]	−1.656

[a] Indicates the optimal lag order according to the selection criterion.

Table 5 – Regression results of the VAR model.

Variables	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)
	ΔCO_2	ΔGDP	ΔInvest	ΔTech
$CO2_{t-1}$	−0.768***	0.629	−0.184	0.986**
	(0.00323)	(0.160)	(0.750)	(0.0127)
$CO2_{t-2}$	−0.835***	−0.0358	−0.373	1.508***
	(5.58e−09)	(0.884)	(0.240)	(0.000)
GDP_{t-1}	−0.314**	−0.158	0.0798	−0.139
	(0.0205)	(0.497)	(0.790)	(0.497)
GDP_{t-2}	−0.393***	0.208	0.234	0.482**
	(0.00285)	(0.358)	(0.422)	(0.0159)
$Invest_{t-1}$	−0.0150	−0.167	0.0975	0.0342
	(0.878)	(0.319)	(0.651)	(0.817)
$Invest_{t-2}$	0.182**	0.177	0.0606	−0.0218
	(0.0267)	(0.207)	(0.739)	(0.861)
$Tech_{t-1}$	−0.448***	0.335	−0.113	0.0520
	(0.00547)	(0.227)	(0.751)	(0.832)
$Tech_{t-2}$	−0.518***	0.217	−0.107	0.935***
	(5.74e−05)	(0.326)	(0.707)	(1.74e−06)
$PolicyC_t$	−0.253***	0.192**	0.249**	0.475***
	(3.59e−06)	(0.0403)	(0.0397)	(9.32e−09)
$PolicyM_t$	0.00599	−0.122*	−0.258***	−0.0535
	(0.883)	(0.0804)	(0.00410)	(0.385)
Constant	0.171***	−0.181**	0.00573	−0.131*
	(0.000139)	(0.0183)	(0.954)	(0.0535)
R-sq	0.887	0.4012	0.646	0.825
Chi-sq	141***	12.1	32.8***	84.7***
	(0.0000)	(0.2792)	(0.0003)	(0.0000)

p-Value is in parentheses.
***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

3.5. Impulse response analyses

For VAR models, the regression coefficients are usually not much interpreted. Instead, impulse response analyses are adopted to examine the directions and magnitudes of the interactions among different variables in the VAR system. With a one-time impulse of a certain variable, all other variables will deviate from, and then return to their equilibriums (Greene, 2011; Hamilton, 1994). Fig. 5 shows the results of the impulse response functions.

With a one-unit increase in the innovation of variable ΔGDP at step 0 and all other innovations at all steps constant, the variable ΔCO2 will move away in the negative direction from the equilibrium at step 1, and gradually return to the equilibrium. This indicates that acceleration in GDP growth rate will first cause acceleration in CO_2 emission reduction.

Table 6 – Results of Granger causality test.

Dependent variable	Independent variable			
	ΔCO_2	ΔGDP	ΔInvest	ΔTech
ΔCO_2	–	51.3***	5.59*	17.3***
	–	(0.000)	(0.061)	(0.000)
ΔGDP	2.00	–	1.87	1.69
	(0.367)	–	(0.393)	(0.429)
ΔInvest	1.47	2.17	–	0.168
	(0.480)	(0.339)	–	(0.919)
ΔTech	53.8***	8.23**	0.0612	–
	(0.000)	(0.016)	(0.970)	–

p-Value is in parentheses.
***, **, and * indicate significance at the 1%, 5% and 10% levels, respectively.

Likewise, the acceleration in technological expenditure increase will also bring about acceleration in CO_2 emission reduction. In contrast, the acceleration in investment expansion will mainly cause the acceleration of CO_2 emission increase. With a one-unit increase in the innovation of variable ΔCO2 at step 0 and all other innovations at all steps constant, variable ΔTech will move away in the positive direction from the equilibrium at step 1, and gradually return to the equilibrium. This indicates that the slowing down of CO_2 emission reduction or the acceleration of CO_2 emission increase will cause the acceleration of technological expenditure increase in future phases. The acceleration in GDP growth rate will accumulate an obvious negative impact on technological expenditure increase at step 3. There is a minor response of ΔTech to the impulse of ΔInvest.

4. Discussion

4.1. CO_2 abatement, investment, and technological expenditure in the iron and steel industry

The VAR regression results, Granger causality test and impulse response analyses all indicated that in China's iron and steel industry, technological expenditure significantly reduced carbon emissions, while investment expansion showed negative effects on carbon emission reduction. Meanwhile, CO_2 emission reduction has a significant effect on technological expenditure of the industry: the pressure for CO_2 abatement promoted the technological expenditure increase in the iron and steel industry. The impact of carbon intensity change on the scale of industrial investment was not significant.

CO_2 emission reduction is usually connected with energy efficiency increase. In China's iron and steel industry, the pressure from CO_2 emission reduction will force a technological expenditure increase, because of the tightening of environmental regulation, the appraisal of governments based on energy conservation and emission reduction performance, and rising energy prices. The incentive-based measures and policies as well as other profitability considerations also strengthen the bi-directional connections between carbon emission reduction and technological innovation.

4.2. Economic growth and the iron and steel industry

VAR regression results, Granger causality test and impulse response analyses indicated that good economic conditions favored carbon emission reduction in China's iron and steel

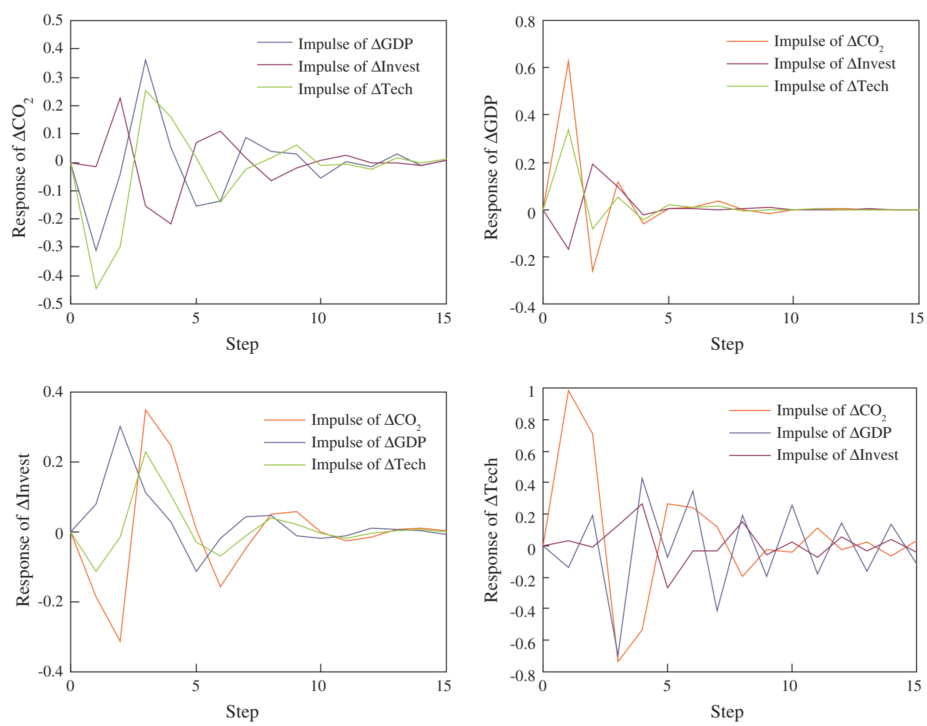

Fig. 5 – Results of impulse response analyses.

industry, and had positive effects on its technological expenditure increase. At the current stage, maintaining a steady, rapid growth of the economy plays a positive role in carbon emission reduction and innovation for the iron and steel industry. ΔCO2 did not have a significant impact on ΔGDP, and it did not Granger-cause ΔGDP, indicating that achieving CO_2 emission reduction in this industrial sector did not necessarily threaten economic growth. This result suggested that a certain degree of decoupling emerged between China's economic growth and the CO_2 emissions of the iron and steel industry.

The demand increase from economic growth did not exhibit a prominent influence on the carbon intensity of the iron and steel industry. This may be due to the effective transition from extensive growth to intensive growth in China's economy. In addition, the iron and steel industry has reached a certain level of technology with plenty of spare capacity. The increase in steel demand from accelerating GDP growth is met by utilizing the spare capacity at a relatively stable and high level of technology, so that its impact on carbon intensity (rather than total CO_2 emissions) is not significant.

In China, GDP growth rate has long been regarded as one of the most important social and economic development goals, governmental objectives and the vane of the economic climate. It provides an important signal effect on industrial and corporate investment decisions and governmental policy adjustments. Economic upturn can provide richer resources and more favorable conditions for industrial technological innovation, leading to positive impacts on carbon emission abatement in industry.

4.3. Policy influence on CO_2 abatement in the iron and steel industry

Policy impacts on the development and carbon emission reduction of China's iron and steel industry have shown different stages. The year 2000 was found to be a turning point, as we anticipated. PolicyC_t had a significant impact on changes in carbon intensity as well as investment scales and technological expenditure, indicating a positive effect on emission reduction and industrial innovation from policies after 2000. In contrast, PolicyM_t had a significant impact on investment scales, but its influences on the changes in technological expenditure and carbon intensity were not verified. The year 2006 was not verified as a turning point.

Before 2000, the government was maintaining an encouraging policy on the iron and steel industry, which tolerated the extensive expansion of the industry. The direction of policies started to turn in late 1999, when the government put forward a new approach on the iron and steel industry. It emphasized "overall control, structural adjustment, efficiency improvement", and proposed the new strategy of "eliminating backward technology and accelerating industrial upgrading". In 2000, it first introduced guiding policies on controlling small-scale steel mills, and carried out a series of policies on total control and stopping blind investment, which led the iron and steel industry into a new phase in terms of CO_2 abatement. Policies in the new stage had a positive influence on CO_2 emission cutting, and the increase of investment and technological expenditure. The government issued the first steel industry development plan in the second half of 2005, and for the first time included energy consumption per unit of GDP as a compulsory development target. In addition to continuously tightening the approval of new projects and adopting more stringent and intensive policies on eliminating backward production capacities and controlling pollution, market-based instruments were also introduced, such as subsidies for upgrading energy-saving technologies and differential power pricing. The policies in this new stage had obvious effects on controlling new projects and investment, but their impacts on promoting technological expenditure and lowering CO_2 intensity were less significant.

5. Conclusions and policy implications

Our study targeted the key question concerning the interrelationships between the CO_2 abatement, investment and technological progress of the iron and steel industry, and their connections with the economic growth and policy intervention in China. We put forward a concise conceptual model and an econometric model to conjointly and empirically examine the relationships.

The results of regression, Granger causality test and impulse response analysis indicated that technological expenditure can significantly reduce CO_2 emissions, and that investment expansion showed a negative impact on CO_2 emission reduction. It was also argued with empirical evidence that good economic conditions favored CO_2 abatement in China's iron and steel industry, while achieving CO_2 emission reduction in this industrial sector did not necessarily threaten the economic growth. This shed light on the dispute over balancing emission cutting and economic growth. Regarding the policy aspects, the year 2000 was found to be an important turning point for the policy evolution and the development of the iron and steel industry in China. The subsequent command and control policies had a significant, positive effect on CO_2 abatement.

Policy implications can be drawn from our analyses.

China's iron and steel industry is at the stage of capacity adjustment, technology innovation and carbon emission reduction. Technological expenditure and upgrading should be highlighted, particularly in terms of the technologies having key impacts on carbon emission reduction, making it a major driver for meeting the CO_2 targets of the industry. The proportion of technology-related investment in total investment should be increased, and the industrial expansion mode should be optimized, in order to achieve more positive impacts of investment on carbon emission reduction. Meanwhile, the CO_2 emission reduction targets at the industrial sector level must be strengthened, to force the transformation and upgrading of the industrial sector.

At the current stage, maintaining steady, rapid economic growth of the economy is still of great importance. Therefore, blind restriction on economic growth in the name of industrial transformation and environmental constraints, in fact may turn out to have a negative influence on industrial upgrading and carbon emission reduction. This complicated relationship suggests a more cautious approach in policy design. It requires more attention and discussion from the government, industry and academia.

The coordination and relative stability of various types of policies and objectives will help further strengthen the positive effect from economic growth on technological innovation and carbon emission abatement. A stable expectation should be consolidated. The government should carry out measures to encourage and facilitate industrial innovation and carbon emission reduction, and barriers to fostering innovation should be removed from the system. In this way, sustained economic growth will provide impetus to innovation and CO_2 emission reduction of the iron and steel industry.

Different development stages of the economy and the iron and steel industry have different features and interactions among the studied factors. Full attention should be paid to this stage difference in policy setting and the structural change of the system. The virtuous cycle among investment, technological expenditure and CO_2 abatement should be strengthened through improved institutional arrangements. There are fewer and fewer low-hanging fruits within the current policy setting. Well-crafted market-based instruments, which can provide incentives for further emission reduction and help achieve a win–win between the economic growth and emission cutting, should be put into practice quickly.

This research focused on the macro level; further studies can be done at the micro-level of iron and steel companies, to explore the possible influences of the GDP growth rate on corporate investment and innovation decisions, and their connections with corporate CO_2 emission reduction. China is continually enacting new policies and tightening existing regulations associated with emission reduction in the iron and steel industry. In particular, the government is now determined to carry out iron-fist measures to fight against air pollution. Facilities in steel mills are forced to shut down, and the elimination of backward production capacity is accelerated. This will have direct and substantial impacts on the development and carbon emission reduction of the industry and the whole economy. Future research should give full attention to the new trends of influential policies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jes.2014.04.020.

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